Exclusive J/ψ photoproduction in pp and PbPb UPC collisions to NLO pQCD

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Outline

- Introduction

  -Set up and general motivation

Part I: Exclusive J/psi production in *conventional* collinear factorisation at NLO

- Pb+Pb UPCs
- Amplitude structure

Based on arXiv:2203.11613

Eskola, CAF, Guzey, Löytäinen, Paukkunen, 22

  -Scale dependence at NLO
  -LO and NLO real and imaginary part
  -Interplay of quark and gluon NLO amplitudes
  -Comparison to data

Part II: Exclusive J/psi production in *tamed* collinear factorisation at NLO

- pp UPCs (so far)
- Amplitude structure

Based on arXiv:1908.08398, 2006.13857

CAF, Martin, Ryskin, Teubner, 20

  -GPDs, resummation, Q_0 cut

- Comparison of new and improved theory with data & extraction of low x gluon PDF

Introduction

- Inclusive processes do not well constrain small x/Regge limit domain of PDFs
- Exclusive processes offer sensitive probe of this domain but as of yet not included in global analyses PDF determination - why?
    1. Off forward kinematics imply susceptibility to *GPD* over conventional PDFs
    2. Reliability and stability of theoretical predictions

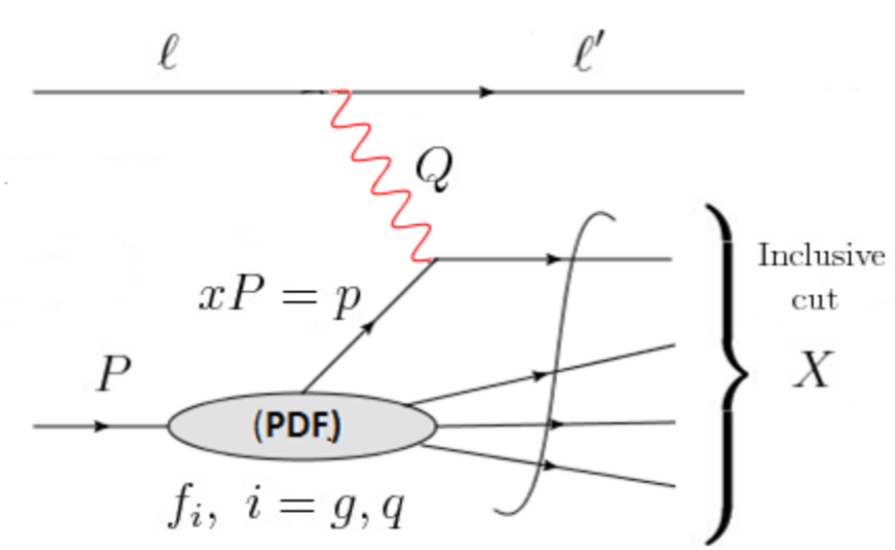
- As higher CM energies are realised at LHC, pushed towards small x domain, W ~ 1/x

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}(\gamma^* p)\bigg|_{t=0} = \frac{\Gamma_{ee}^{J/\psi} M_{J/\psi}^3 \pi^3}{48\alpha_{\mathrm{em}}} \left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} R_g x g(x, \bar{Q}^2)\right]^2 \left(1 + \frac{Q^2}{M_{J/\psi}^2}\right)$$

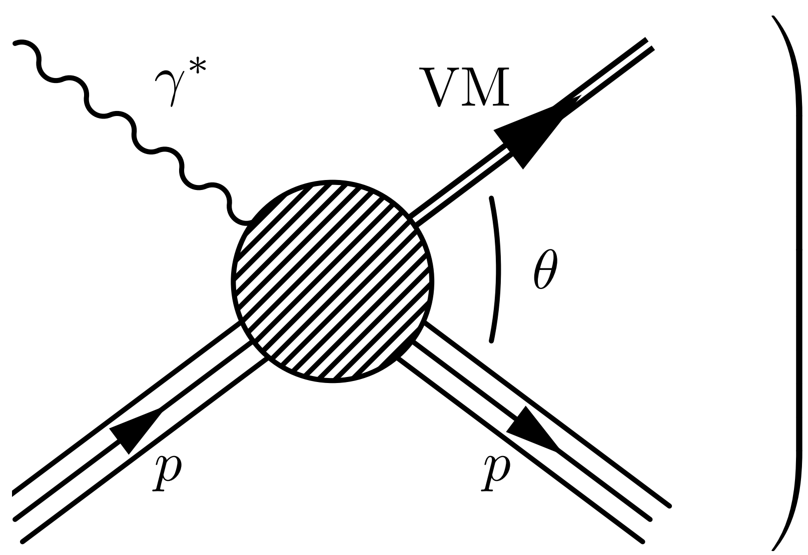
Ryskin 1993

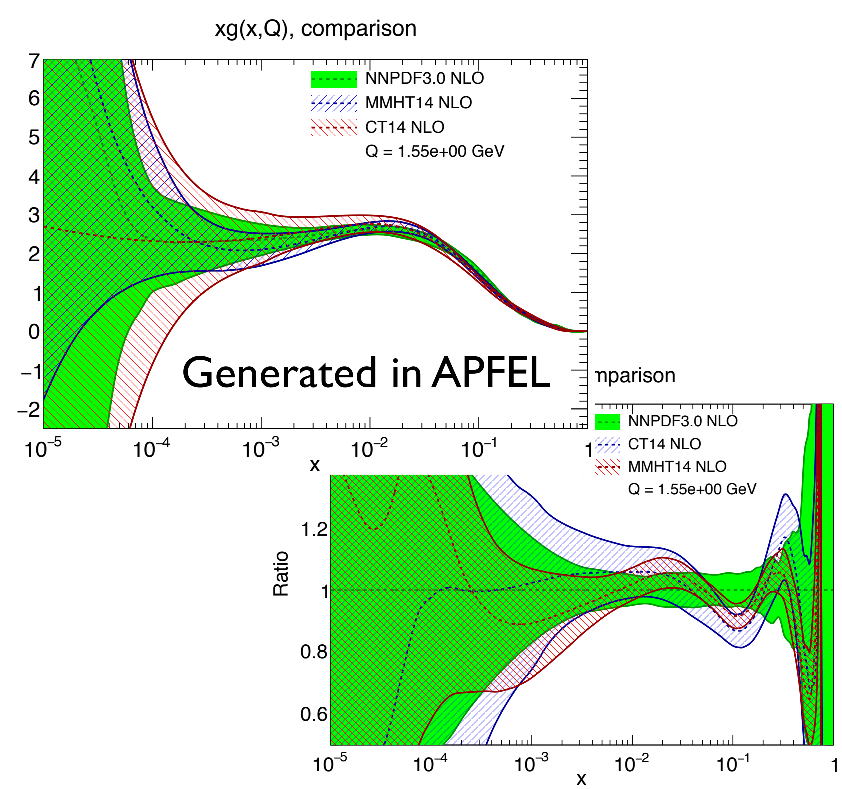
Inclusive - included in global parton analyses

Exclusive - can we use the data?



e.g. DIS



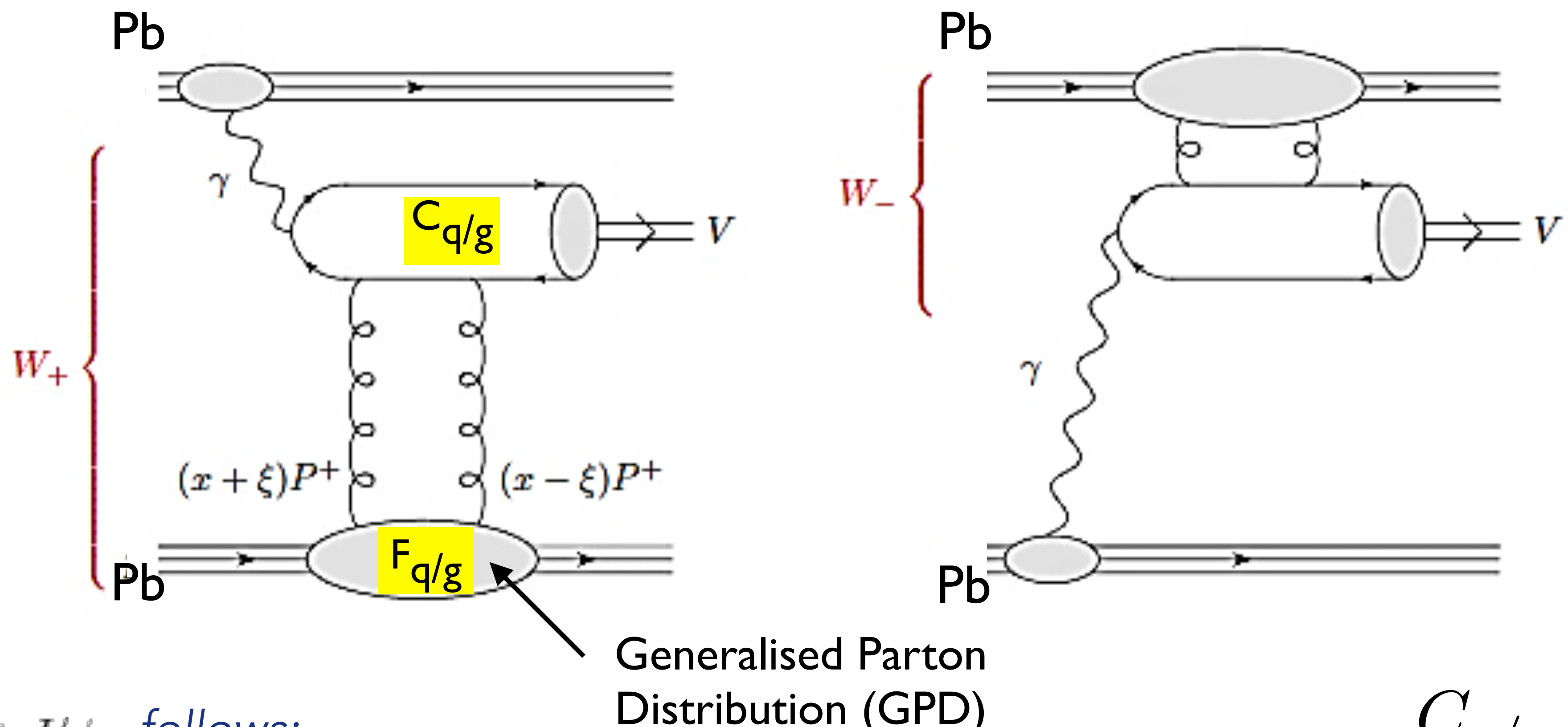


Part I

Part I: Exclusive J/psi production in *conventional* collinear factorisation at NLO

General Set up and assumptions

Exclusive J/psi photoproduction in Pb+Pb UPC collisions in *conventional* collinear factorisation



Setup for $\gamma p \to J/\psi p$ follows:
Ivanov, Schäfer, Szymanowski, Krasnikov, 04

- Factorisation: $F_{q/g} \otimes C_{q/g} \otimes \phi^V_{Q\bar{Q}}$
- Leading zeroth order term in rel. velocity (NRQCD)
- Colour singlet exchange between hard and soft sectors

$$A \propto \int_{-1}^{1} \mathrm{d}x \left[C_g(x,\xi) F_g(x,\xi) + \sum_{q=u,d,s} C_q(x,\xi) F_q(x,\xi) \right]$$

$C_{q/g}$

Photoproduction:
- hep-ph/0401131

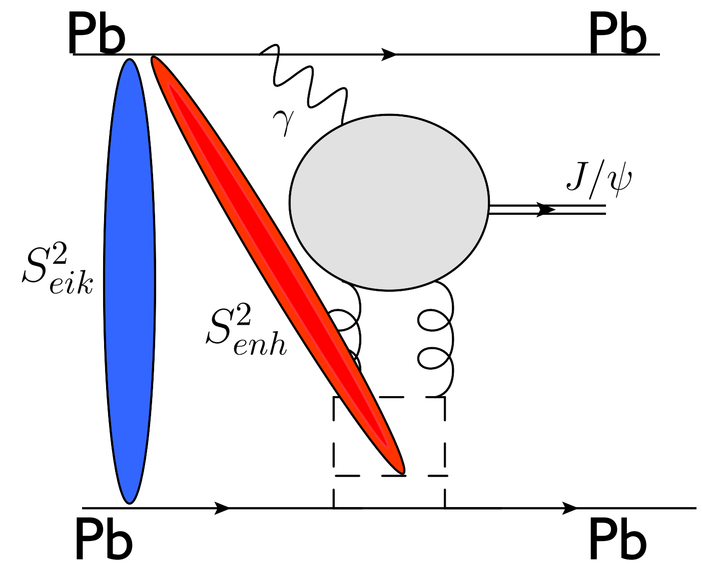
Ivanov, Schäfer, Szymanowski, Krasnikov, 04

Electroproduction:
- arXiv:1903.00171
- arXiv:2105.07657

Chen, Qiao, 19
CAF, Gracey, Jones, Teubner, 21

Framework

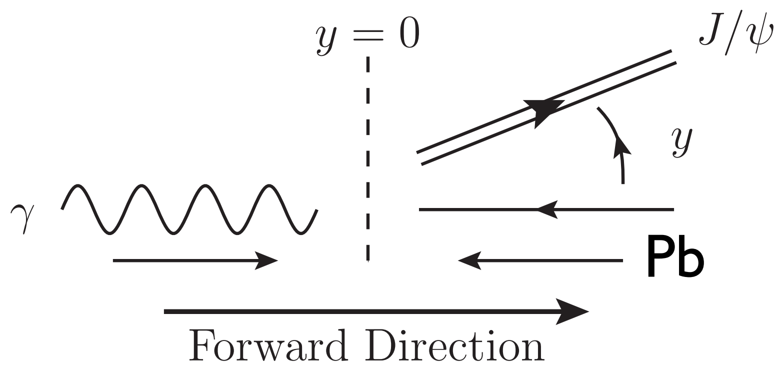
Rapidity differential cross section:



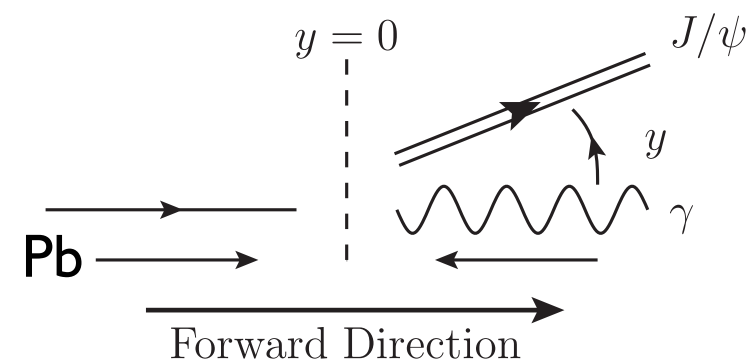
$$\frac{d\sigma^{AA\to AVA}}{dy} = \left[k\frac{dN_\gamma^A(k)}{dk}\sigma^{\gamma A\to VA}(k)\right]_{k^-} + \left[k\frac{dN_\gamma^A(k)}{dk}\sigma^{A\gamma\to AV}(k)\right]_{k^+}$$

Photon flux / survival factor

For a given rapidity y, have photons of energy $k_\pm = \frac{M_{J/\psi}}{2}\exp(\pm y)$ in configuration $W_\pm$



W_+



W_-

Hard scattering cross section:

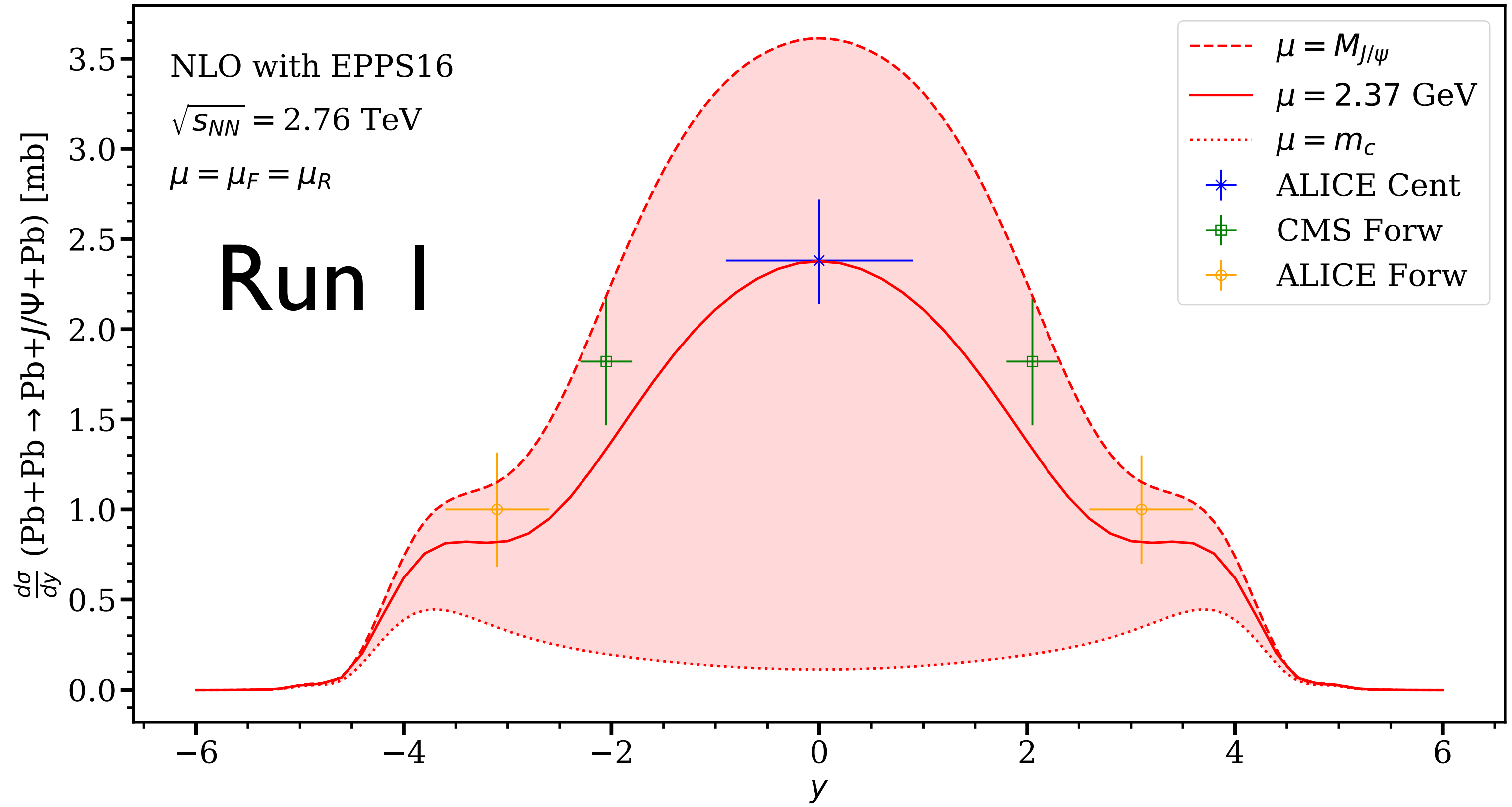
$$\sigma^{\gamma A\to VA} = \left.\frac{d\sigma^{\gamma N\to VN}}{dt}\right|_{t=0}\int_{t_{min}}^{\infty} dt' \, |F_A(-t')|^2$$

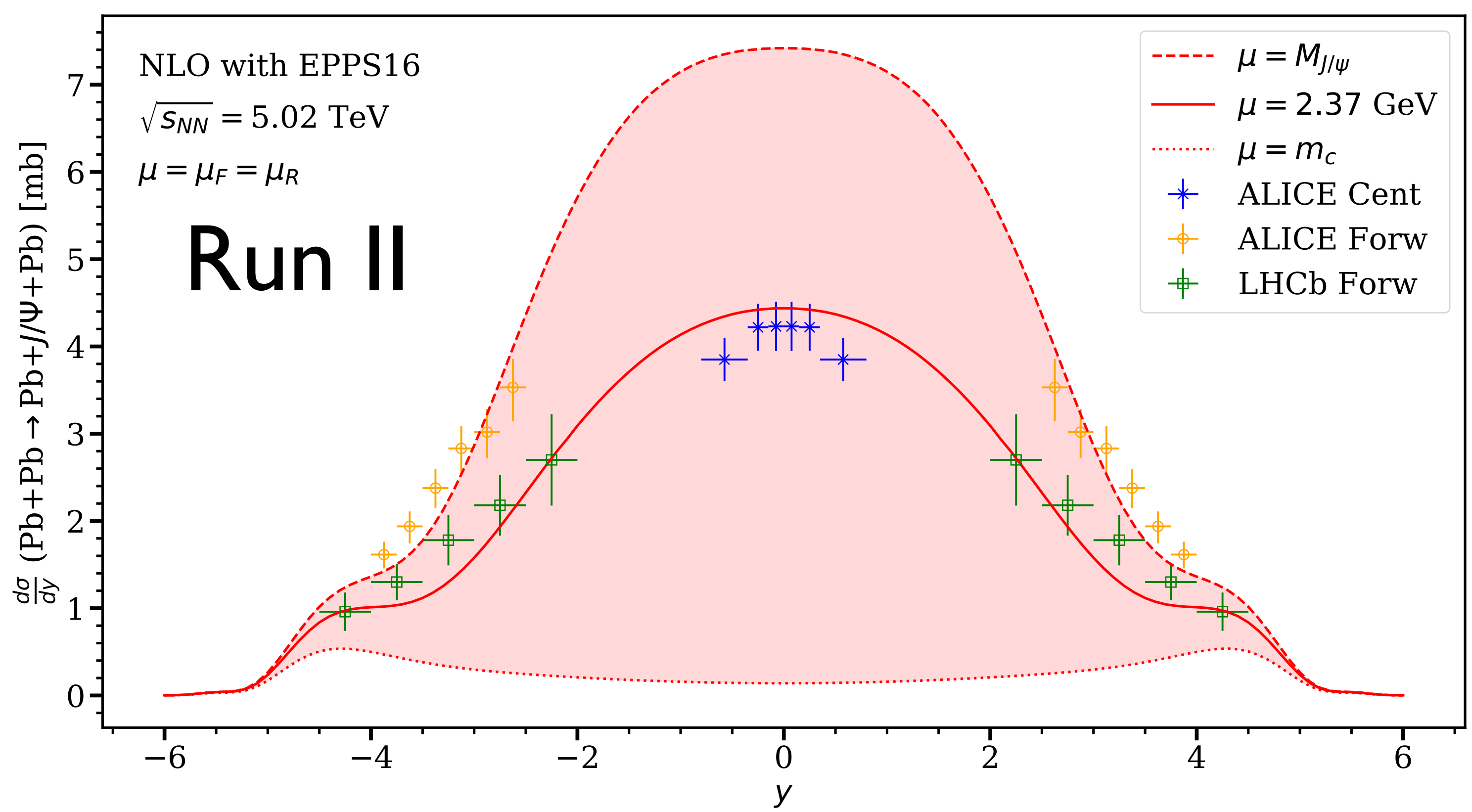
Nuclear form factor

Baseline: GPDs in forward limit

Numerical results checked in two different ways

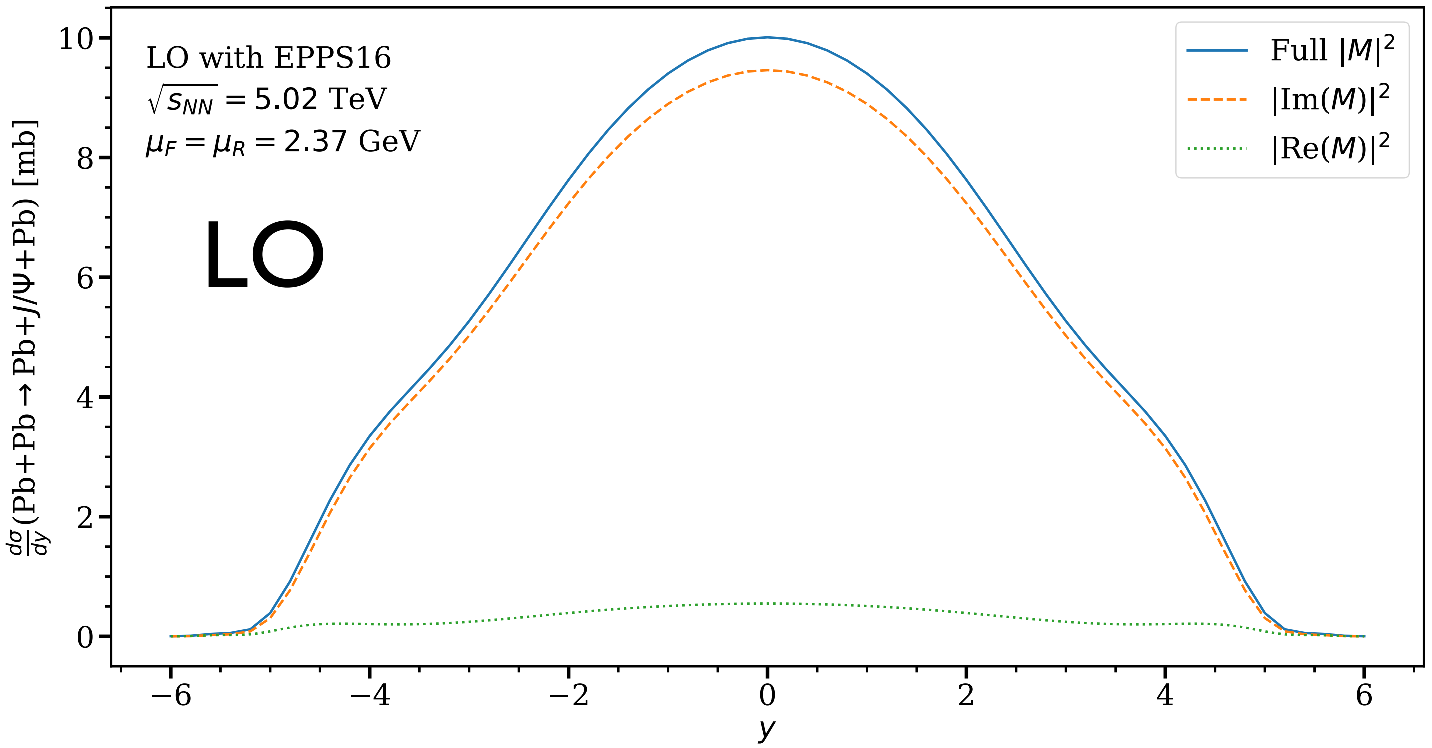
Scale dependence at NLO



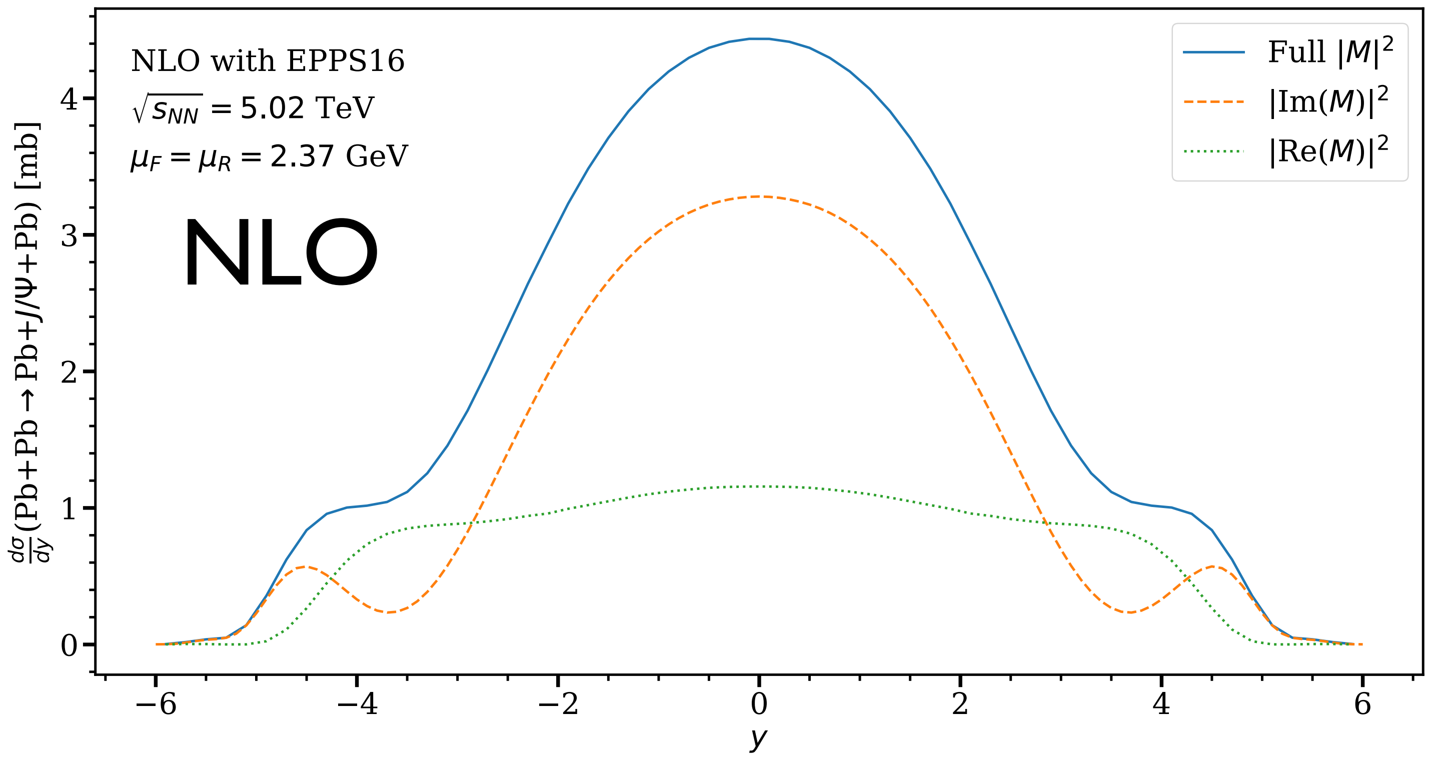


- Scale dependence large (!)
- ‘Optimal scale’: fitted to reproduce the data at both Run I and Run II energies
- Large scale variation consistent with results in hep-ph/0401131

Decomposition LO and NLO Re and Im

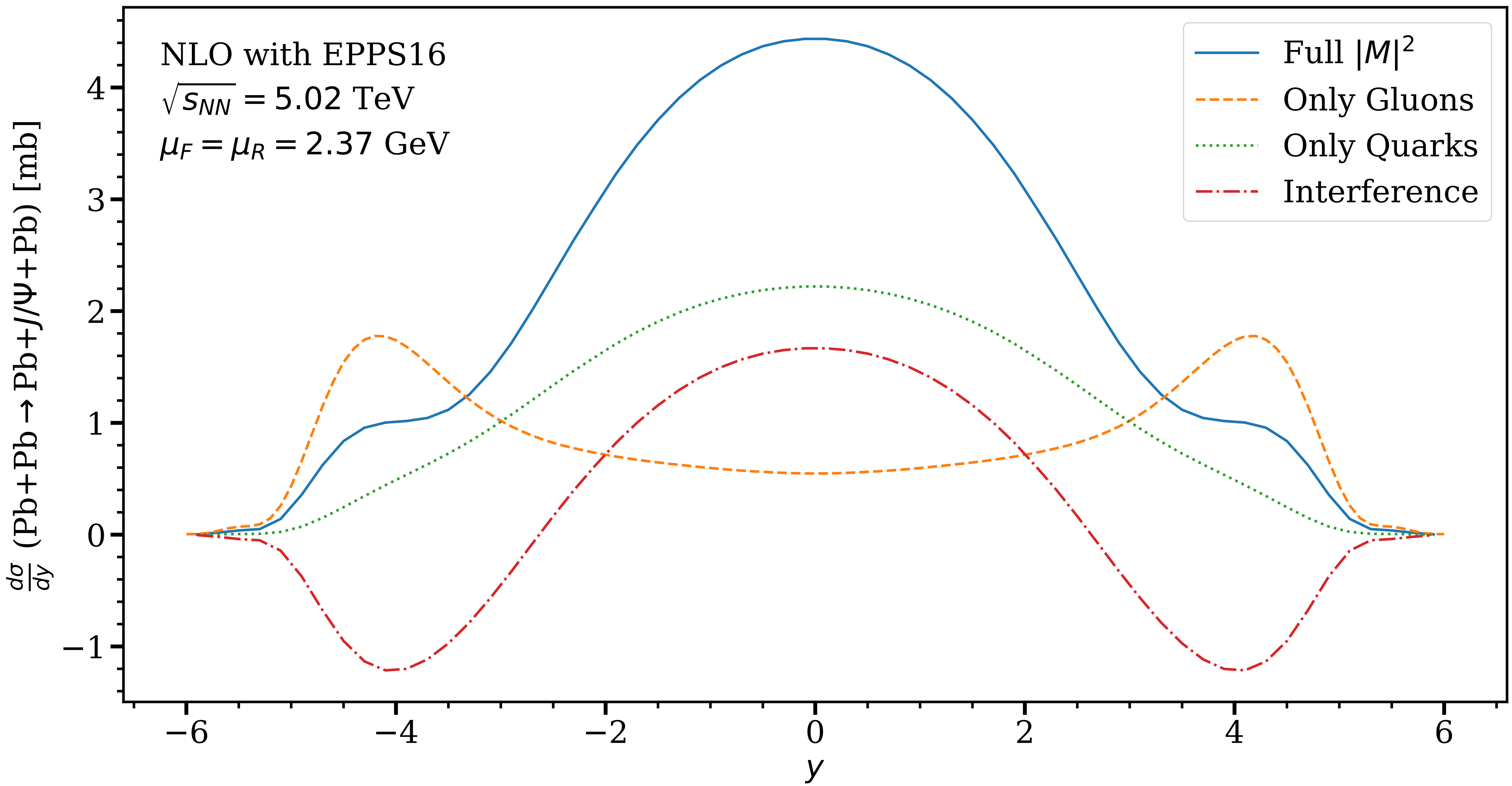


- At LO imaginary part of amplitude dominates



- At NLO, real part not negligible
- See also hep-ph/0401131

Interplay of quark and gluon at NLO

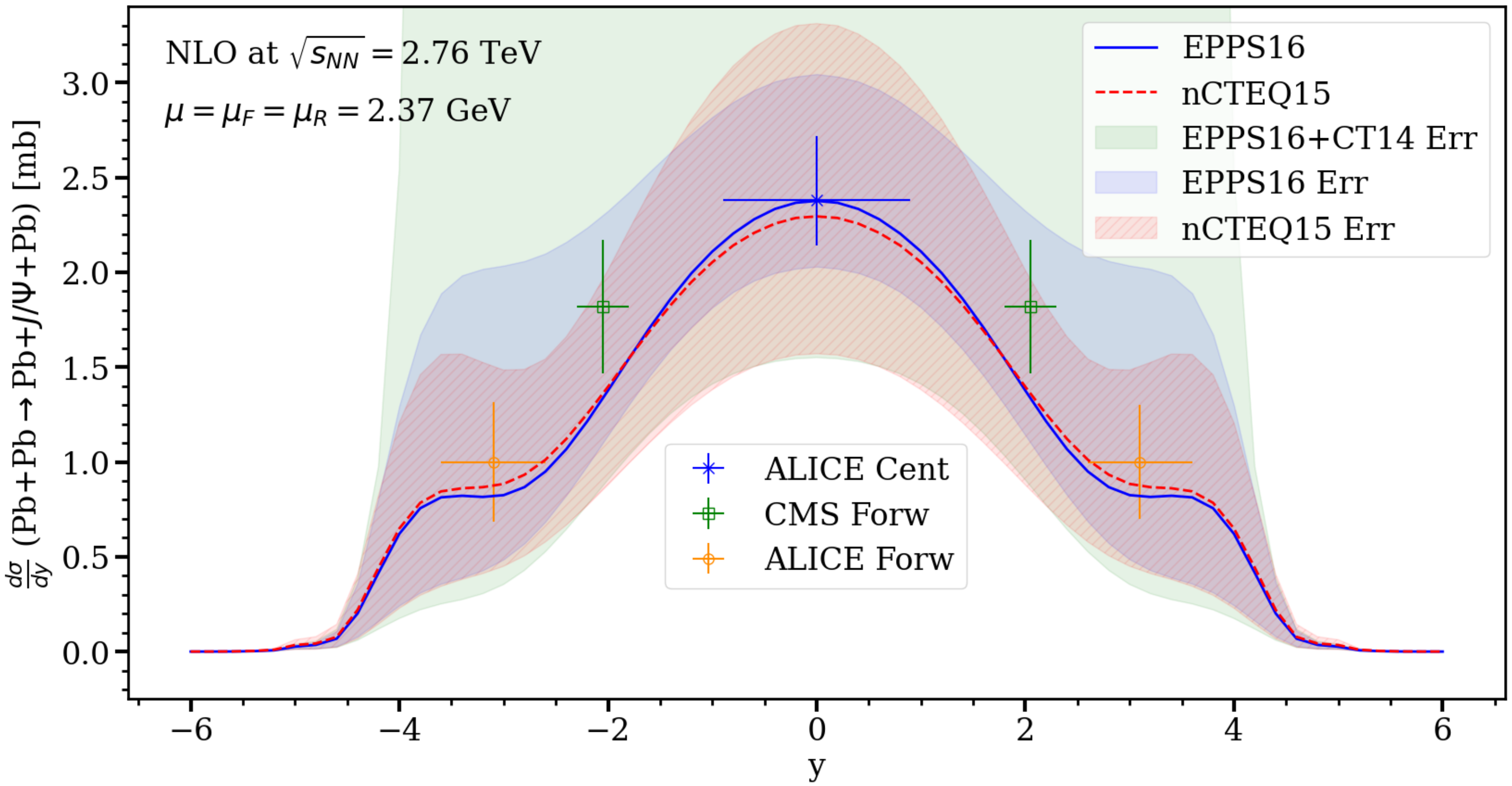


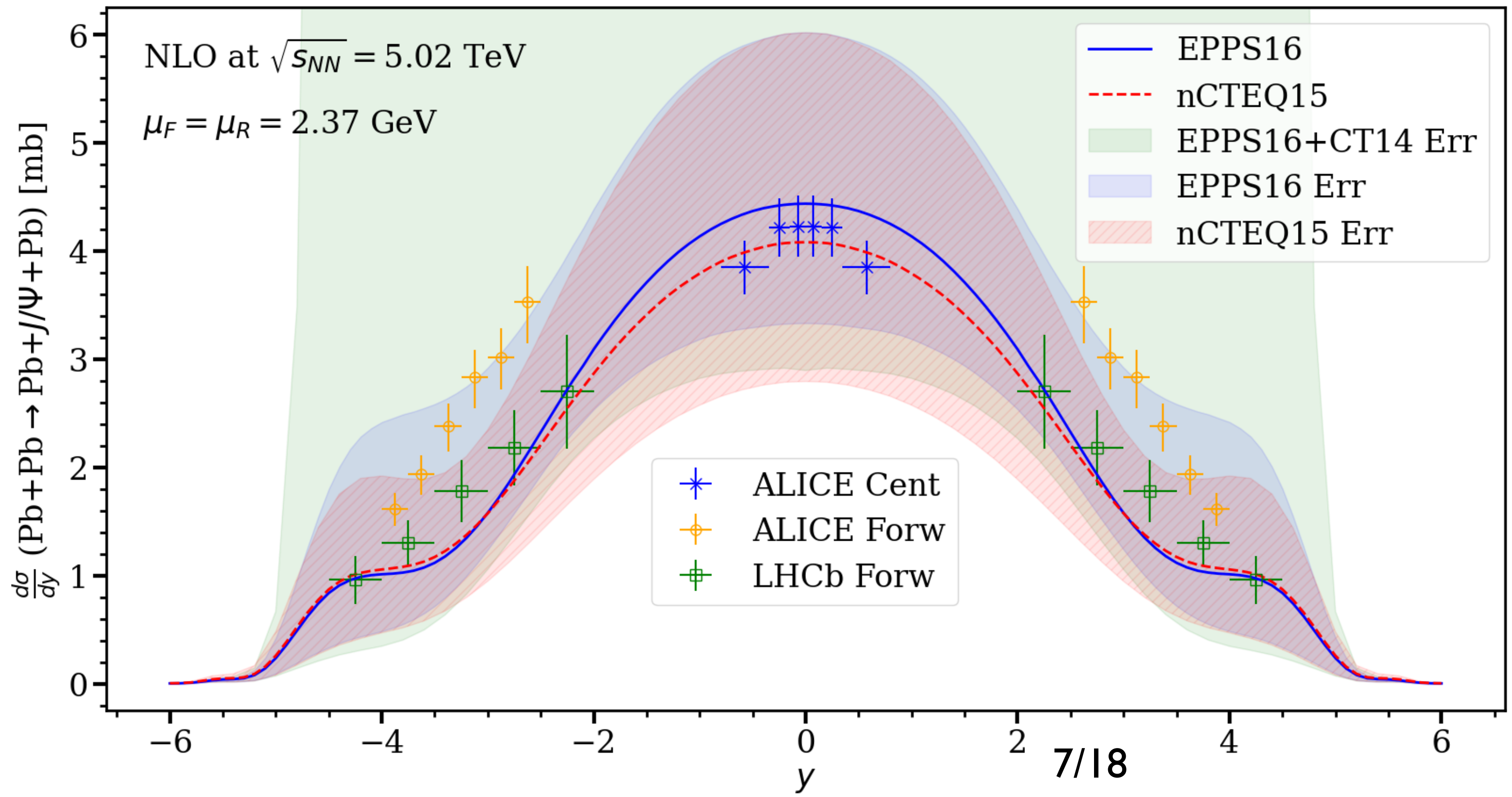
Quark contribution dominant at mid-rapidity (!)

Structure of amplitude detailed, interplaying between photoproduction cross section, photon flux, form factor and $W_\pm$ components

Key: Cancellation of LO and NLO gluon amplitudes due to opp. signs

Comparison with data





- Nuclear uncertainties encompass available data both at Run I and Run II energies nicely
- Free proton uncertainties large and dominated by single error set
- Tension between Run II ALICE and LHCb data at forward rapidities

Part 1: Conclusions and Outlook

- Implementation of NLO collinear factorisation to exclusive photoproduction of J/psi in PbPb UPCs

Noteworthy features:

-*Large* scale dependence

-Quarks dominate at mid rapidity at NLO

→ Discouraging… what use?

- Exclusive J/psi production in a *tamed* collinear factorisation

-Q_0 subtraction and resummation

→ Upshot: all hope not lost!

-*Mild* scale dependence

-Quark contribution small (~0)

See plots →

Framework: Tamed collinear factorisation + Shuvaev(PDF) + NRQCD

-Allowed for a meaningful comparison of new and improved theory prediction with data in pp UPCs and therefore extraction of low x gluon PDF

CAF, Jones, Martin, Ryskin, Teubner, 1908.08398 & 2006.13857

-Extend refined framework built originally for p+p to Pb+Pb

…extension to p+Pb in this framework, CAF, Jones, Martin, Ryskin, Teubner, *in preparation*

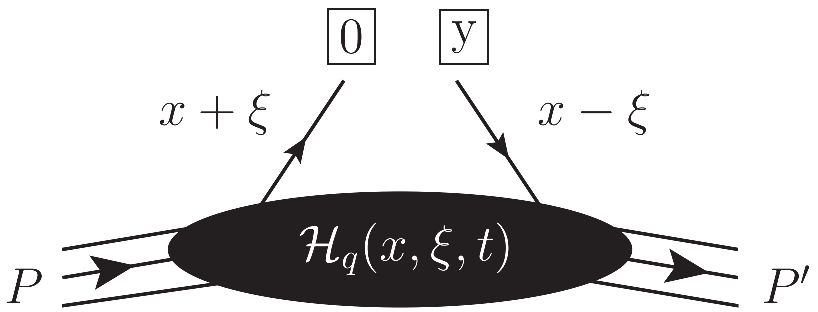
Part II

Part II: Exclusive J/psi production in *tamed* collinear factorisation at NLO

GPDs and the Shuvaev transform

GPDs generalise PDFs: outgoing/incoming partons carry different momentum fractions

Müller 94; Radyushkin 97; Ji 97



$$\langle P'|\,\overline{\psi}_q(y)\mathcal{P}\{\}\psi_q(0)\,|P\rangle$$

Shuvaev: Relates GPDs to PDFs at small x under physically motivated assumptions c.f analyticity

Shuvaev 99   Martin et al. 09

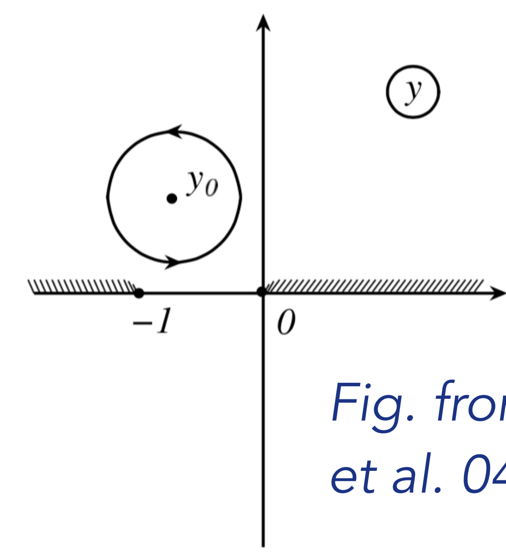


Fig. from Ivanov et al. 04

Idea: Conformal moments of GPDs = Mellin moments of PDFs

(up to corrections of order xi^2)

- Construct GPD grids in multidimensional parameter space x,xi/x,qsq with forward PDFs from LHAPDF
- Costly computationally due to slowly converging double integral transform
- Regge theory considerations => Shuvaev transform valid in space like (DGLAP) region only. In time like (ERBL) region imaginary part of coefficient is zero

Shuvaev Transform

Full Transform:

$$\mathcal{H}_q(x,\xi) = \int_{-1}^{1} \mathrm{d}x' \left[\frac{2}{\pi}\mathrm{Im}\int_0^1 \frac{\mathrm{d}s}{y(s)\sqrt{1-y(s)x'}}\right] \frac{\mathrm{d}}{\mathrm{d}x'}\left(\frac{q(x')}{|x'|}\right),$$

$$\mathcal{H}_g(x,\xi) = \int_{-1}^{1} \mathrm{d}x' \left[\frac{2}{\pi}\mathrm{Im}\int_0^1 \frac{\mathrm{d}s(x+\xi(1-2s))}{y(s)\sqrt{1-y(s)x'}}\right] \frac{\mathrm{d}}{\mathrm{d}x'}\left(\frac{g(x')}{|x'|}\right),$$

$$y(s) = \frac{4s(1-s)}{x+\xi(1-2s)}.$$

[Shuvaev et. al 1999]

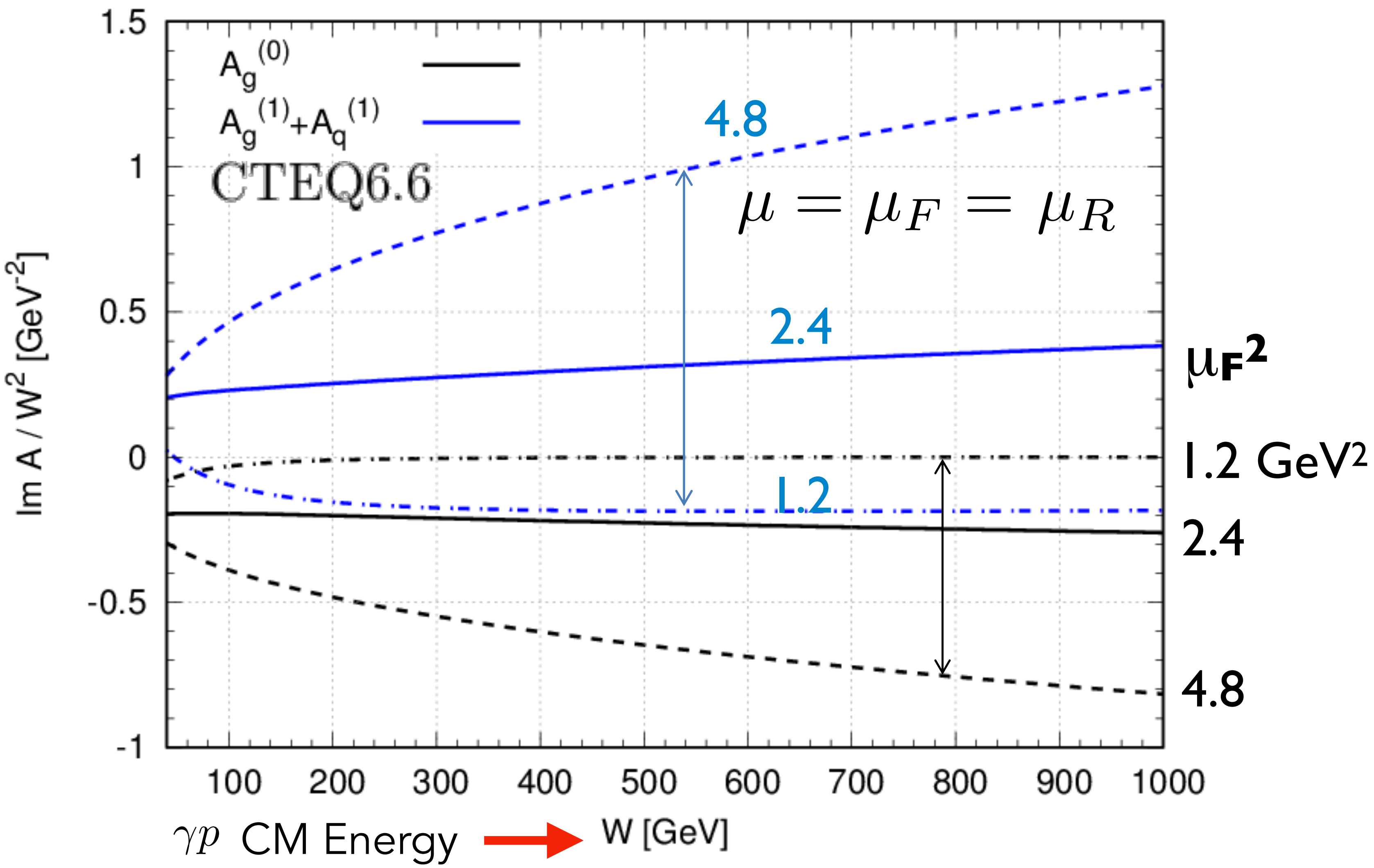
More discussion about derivation in backup

Stability of prediction I

D. Ivanov, B.Pire, L.Szymanowski, J.Wagner, hep-ph/0401131, erratum: arXiv:1411.3750
S.P.Jones, PhD thesis, Liverpool (2014)

NLO in MSbar scheme

A. **Bad perturbative convergence** $|NLO_{correctn.}| > |LO|$ **and opp. sign**
B. **Strong dependence on scale μ_F**



Disclaimer: Plots generated using existing global partons. Here, CTEQ6.6

Can do better…

Stability of prediction I

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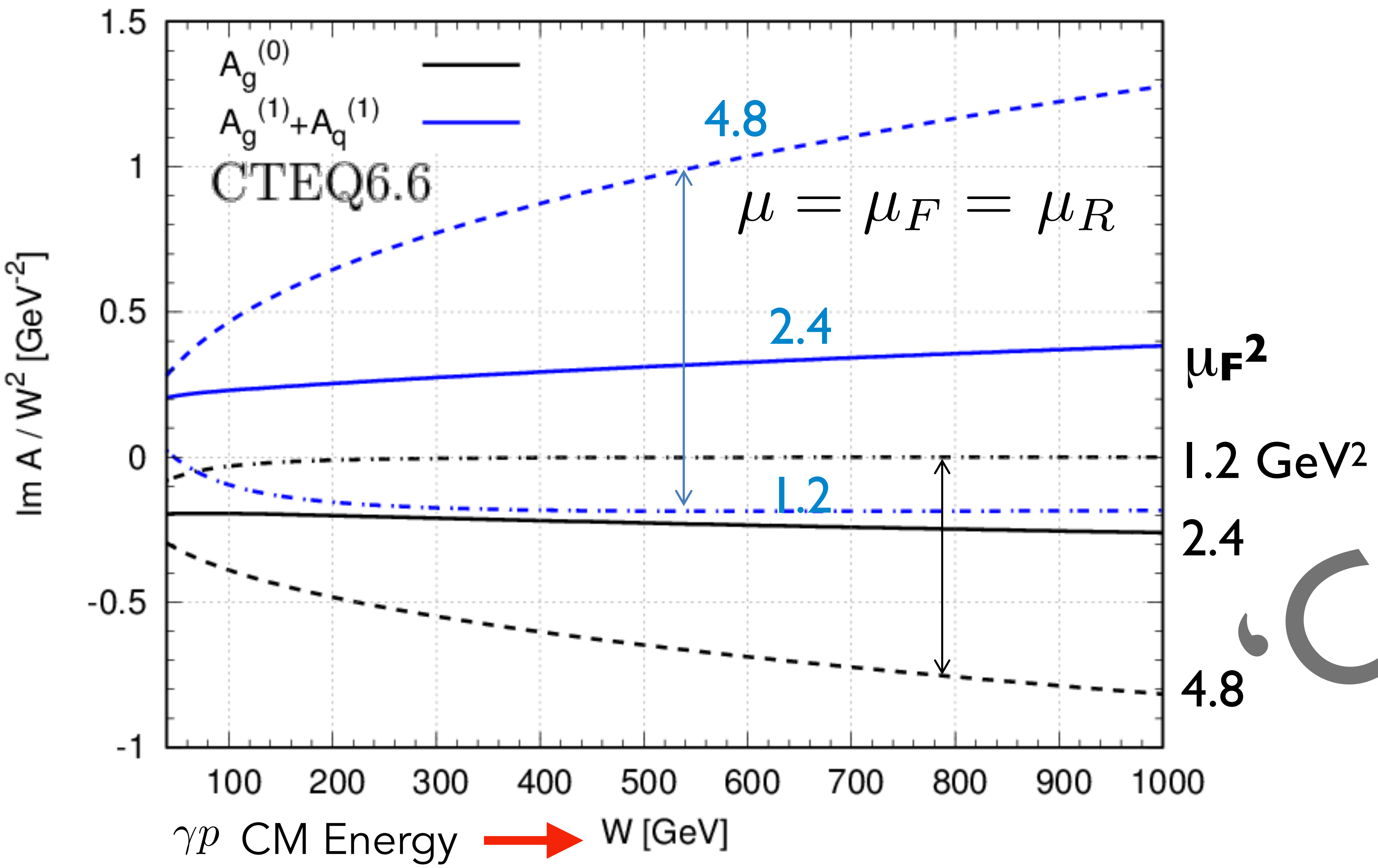


'Conventional'

Disclaimer: Plots generated using existing global partons. Here, CTEQ6.6

Can do better…

Stability of prediction II

'Scale Fixing'

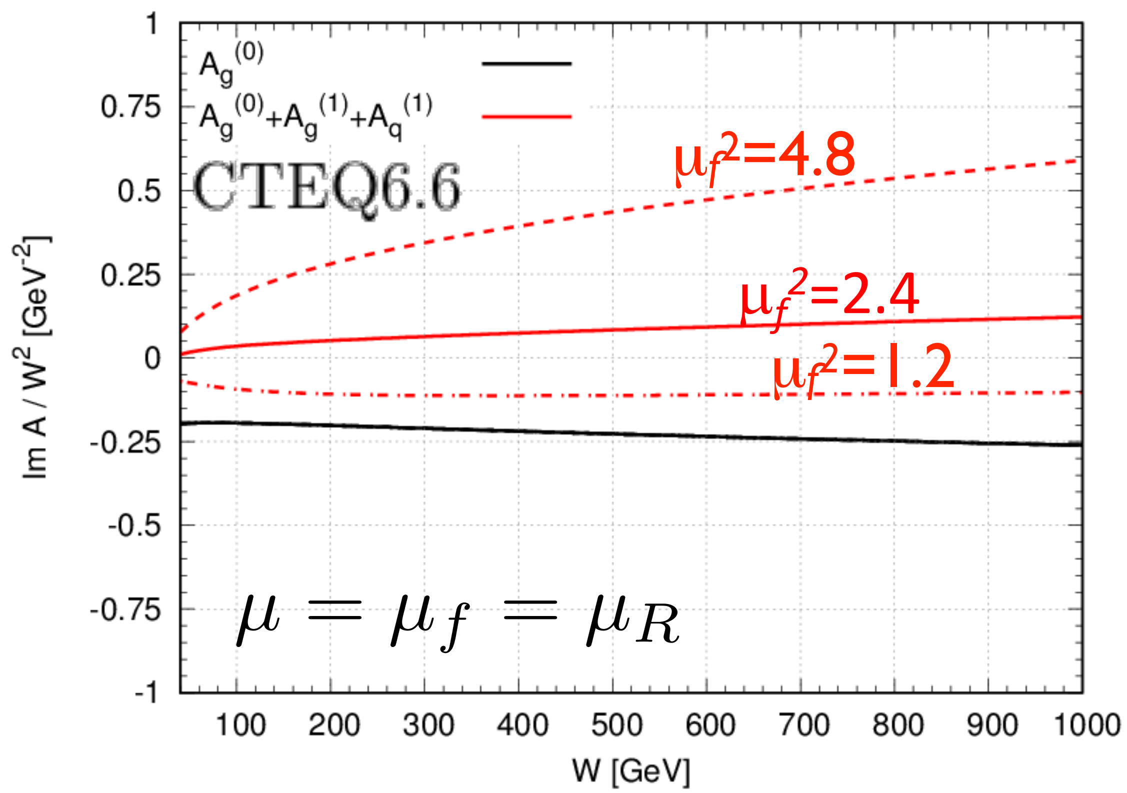
`Optimal' factorisation scale $\mu_F = m$ eliminates large logs at NLO

S.P.Jones, A.D.Martin, M.G.Ryskin, T.Teubner, 1507.06942

Resummation of $(\alpha_S \ln(1/\xi) \ln(\mu_F/m))^n$

terms into LO PDF, leaving remnant NLO coefficient and residual, μ_f, scale dependence

Fix: $\mu_F^2 = 2.4\ \mathrm{GeV}^2$



$$A(\mu_f) = C^{LO} \times GPD(\mu_F) + C^{NLO}(\mu_F) \times GPD(\mu_f)$$

Look for another sizeable correction that can reduce variations further -> implementation of a **`Q0'** cut

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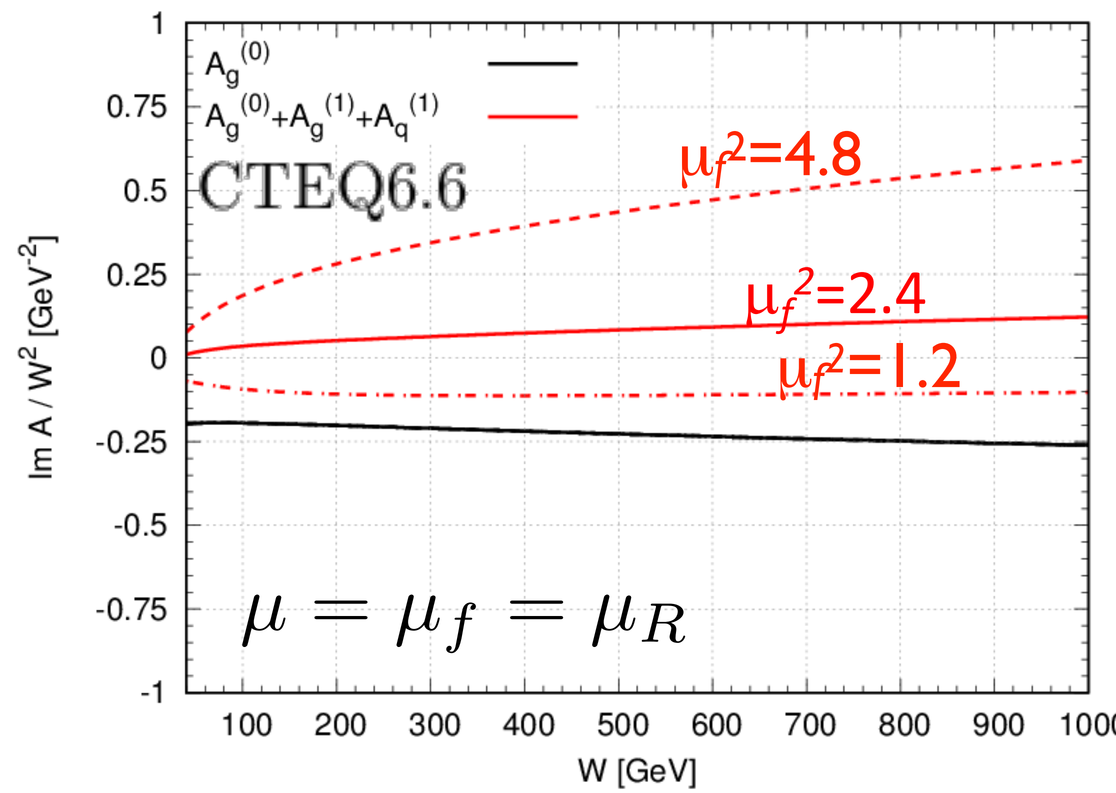


Resummation of $(\alpha_s \ln(1/\xi) \ln(\mu_F/m))$

terms into LO PDF, leaving remnant
NLO coefficient
and residual, μ_f, scale dependence

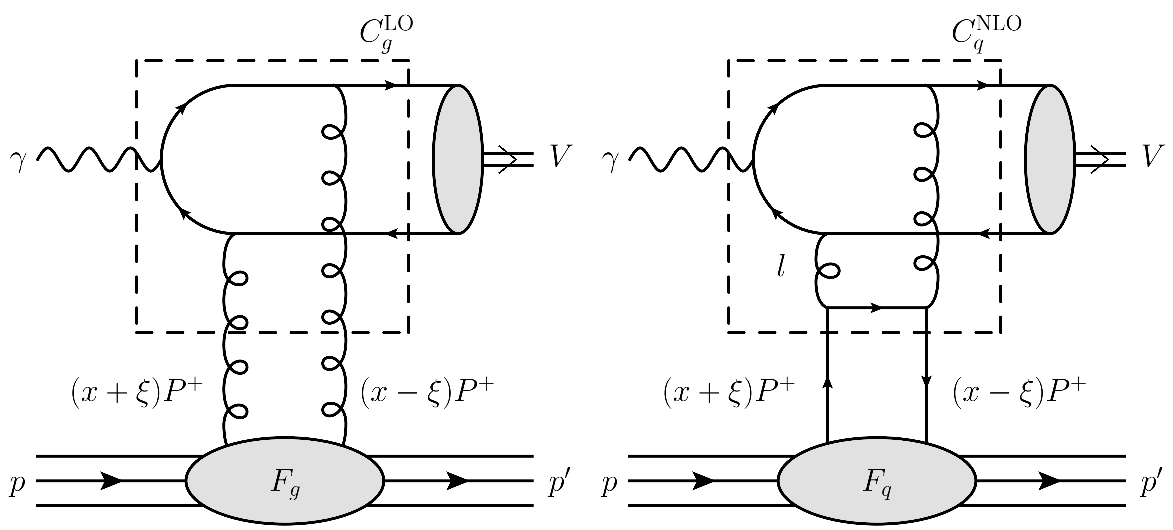
'DL resummed'

$A(\mu_f) = C^{LO} \times GPD(\mu_F) + C^{NLO}(\mu_F) \times GPD(\mu_f)$

Look for another sizeable correction that can reduce variations further
-> implementation of a **`Q0'** cut

Stability of prediction III

`Q0' cut   S.P.Jones, A.D.Martin, M.G.Ryskin, T.Teubner, 1610.02272



Subtract DGLAP contribution

NLO (| ℓ^2 | < Q_0^2)

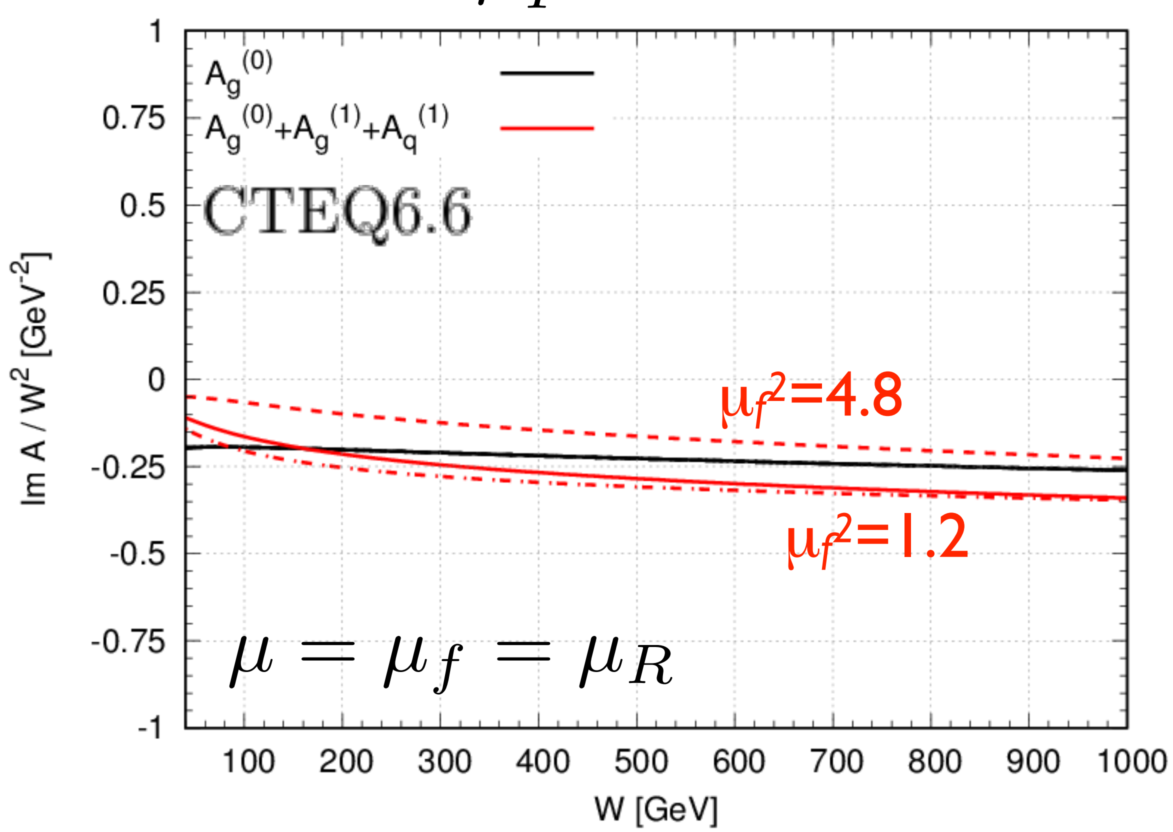
from known NLO MSbar coefficient function to avoid a double count with input GPD at Q_0.

Ubiquitous and typically power suppressed, but sizeable here

$$\mathcal{O}(Q_0^2/M_{J/\psi}^2)$$

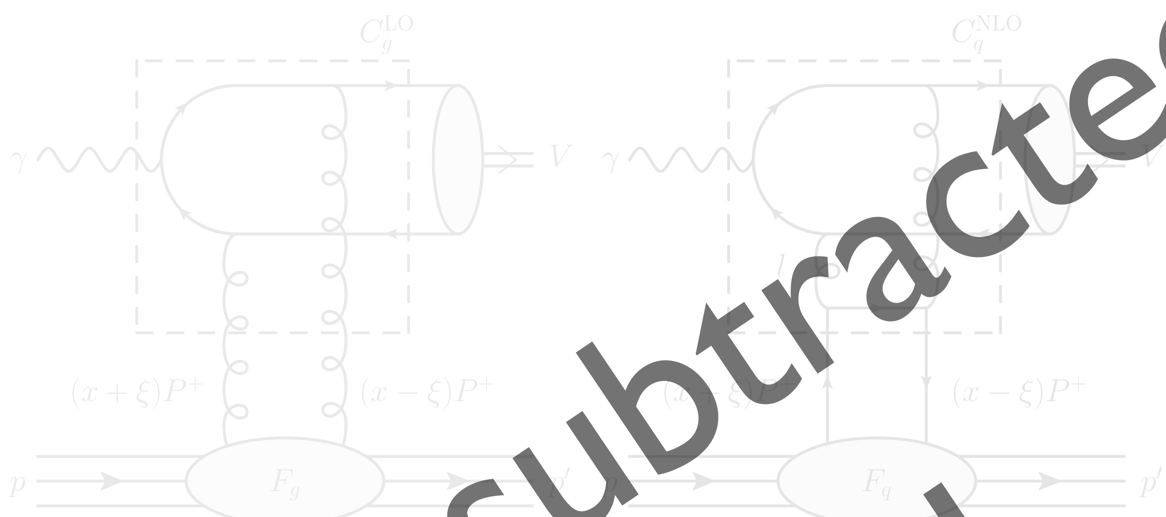
How do these predictions compare with the data at HERA and LHCb?

Fix: $\mu_F^2 = 2.4\ \text{GeV}^2$



Stability of prediction III

`Q0' cut S.P.Jones, A.D.Martin, M.G.Ryskin, T.Teubner, 1610.02272



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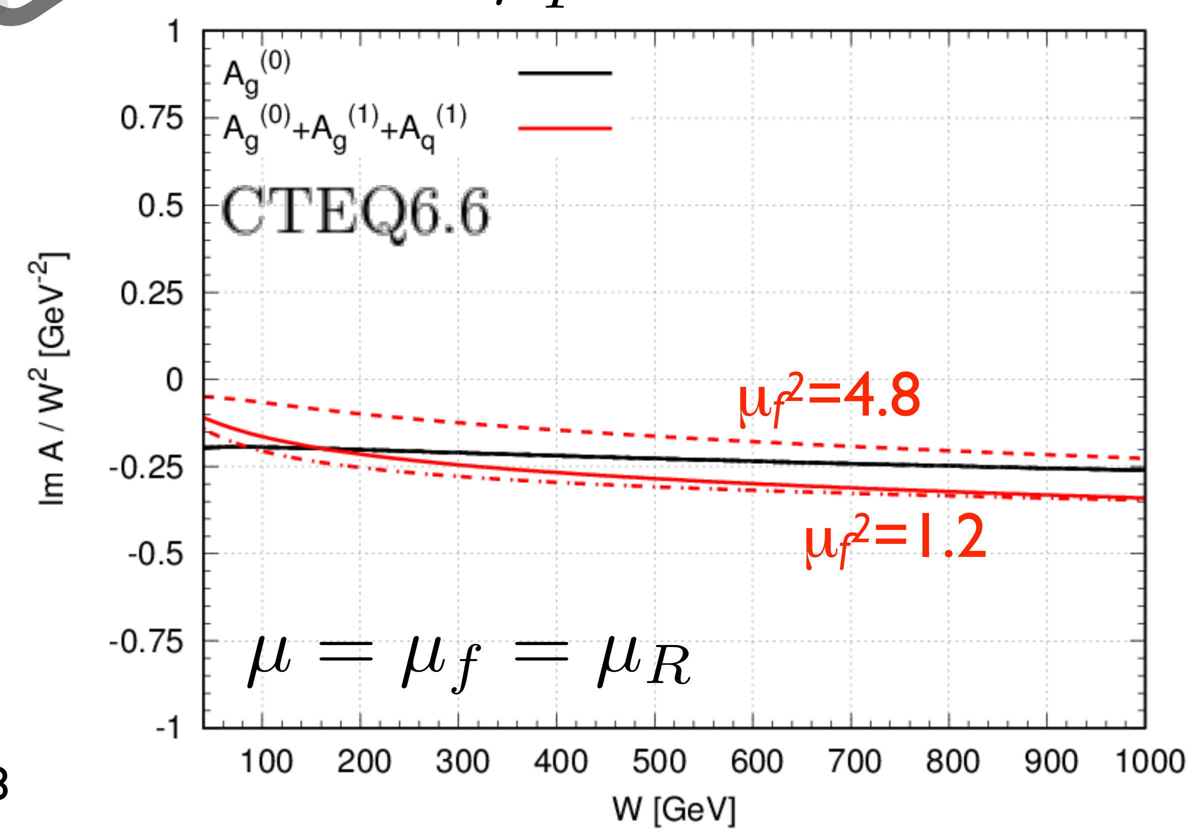
Ubiquitous and typically power suppressed, but sizeable here

$\mathcal{O}(Q_0^2/M_{J/\psi}^2)$

How do these predictions map onto the data at HERA and LHCb?

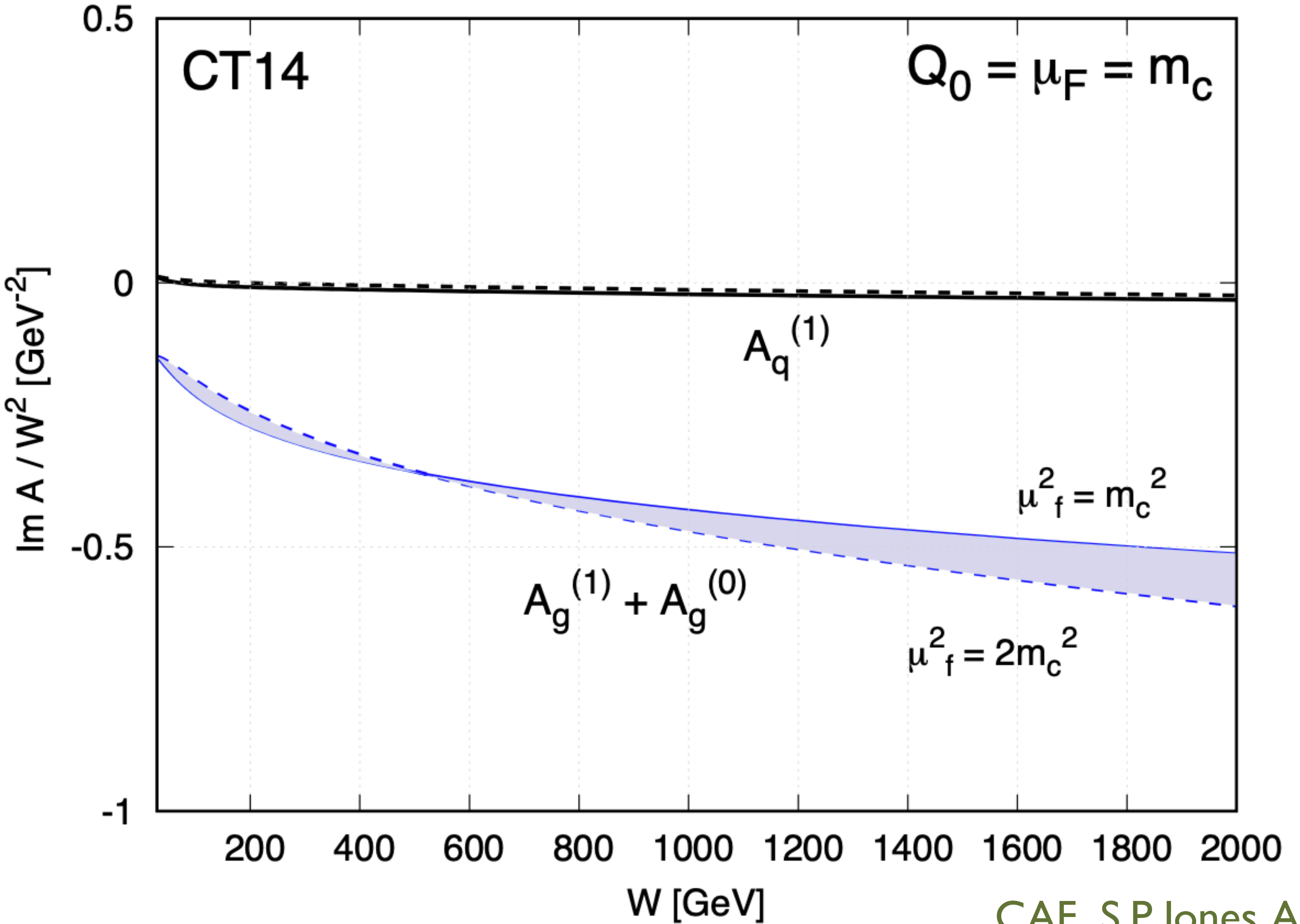
‘Q0 subtracted + DL resummed’

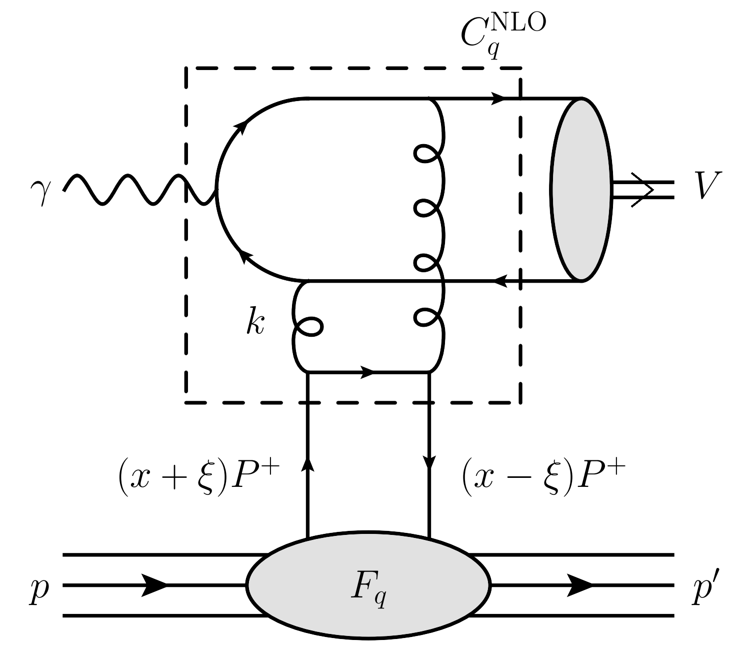
Fix: $\mu_F^2 = 2.4 \text{ GeV}^2$



Interplay of quark and gluons at NLO

After Q_0 subtraction:





CAF, S.P. Jones, A.D. Martin, M.G. Ryskin, T. Teubner, 1908.08398

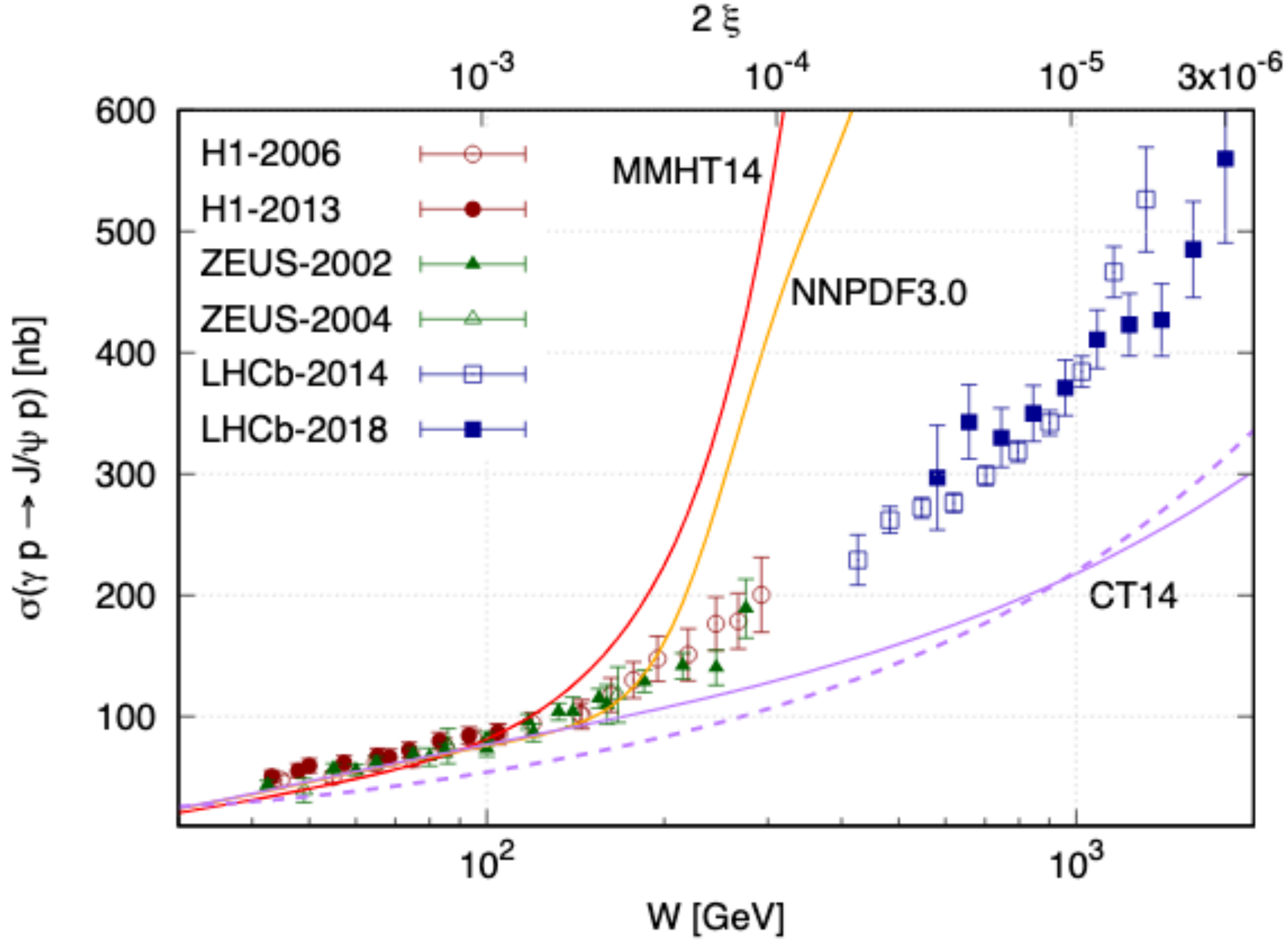
Quark contribution separated from hard scattering by at least *one* step of DGLAP evolution and is therefore removed after imposition of Q_0 subtraction

⟶ Gluon driven again like at LO

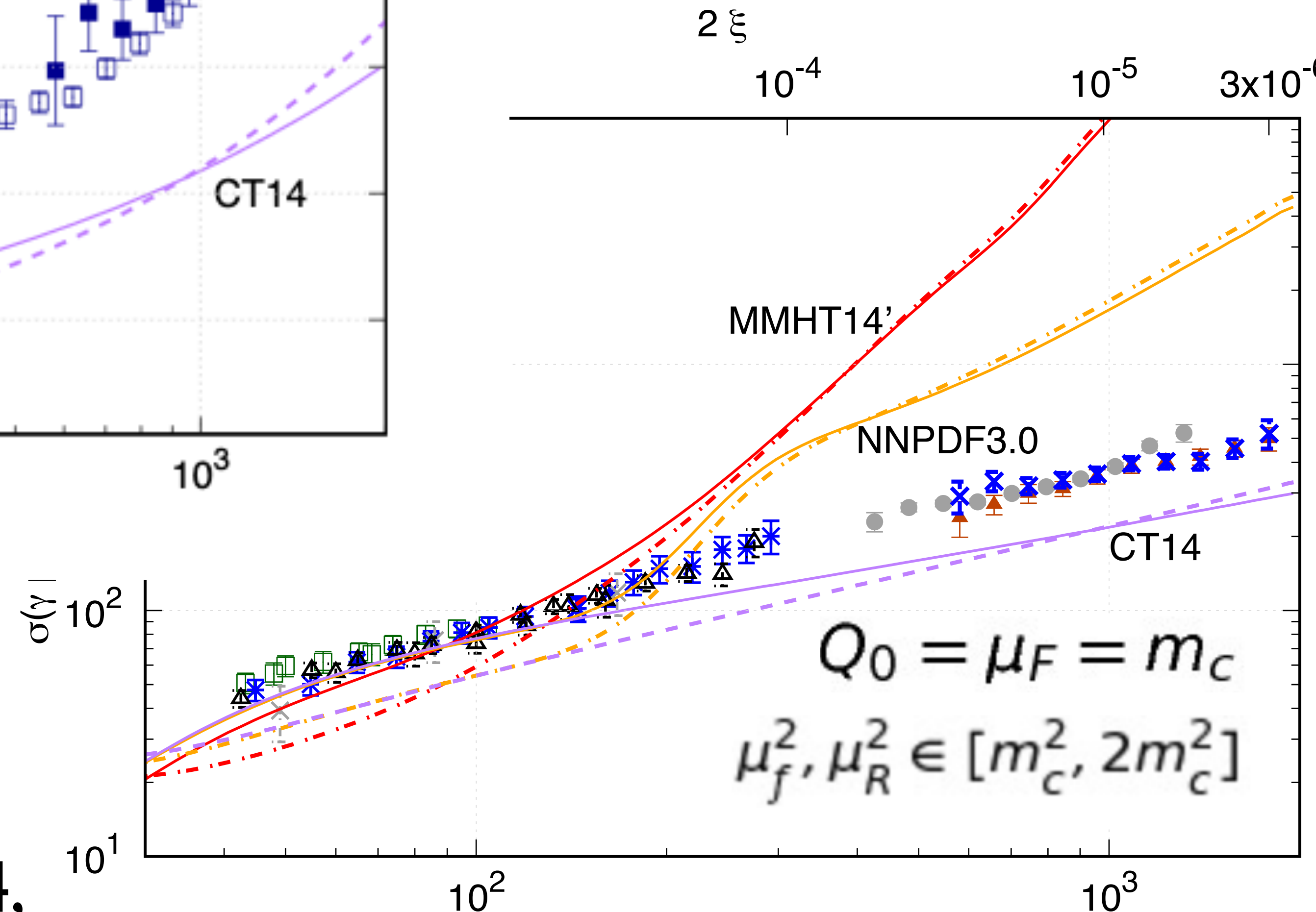
Cross section stability

Plots demonstrates good scale stability of our NLO predictions in LHCb regime

Predictions at optimal scale (solid) agree better with HERA data



CAF, S.P.Jones, A.D.Martin, M.G.Ryskin, T.Teubner, 1907.06471 & 1908.08398



Diversity in prediction -> important message

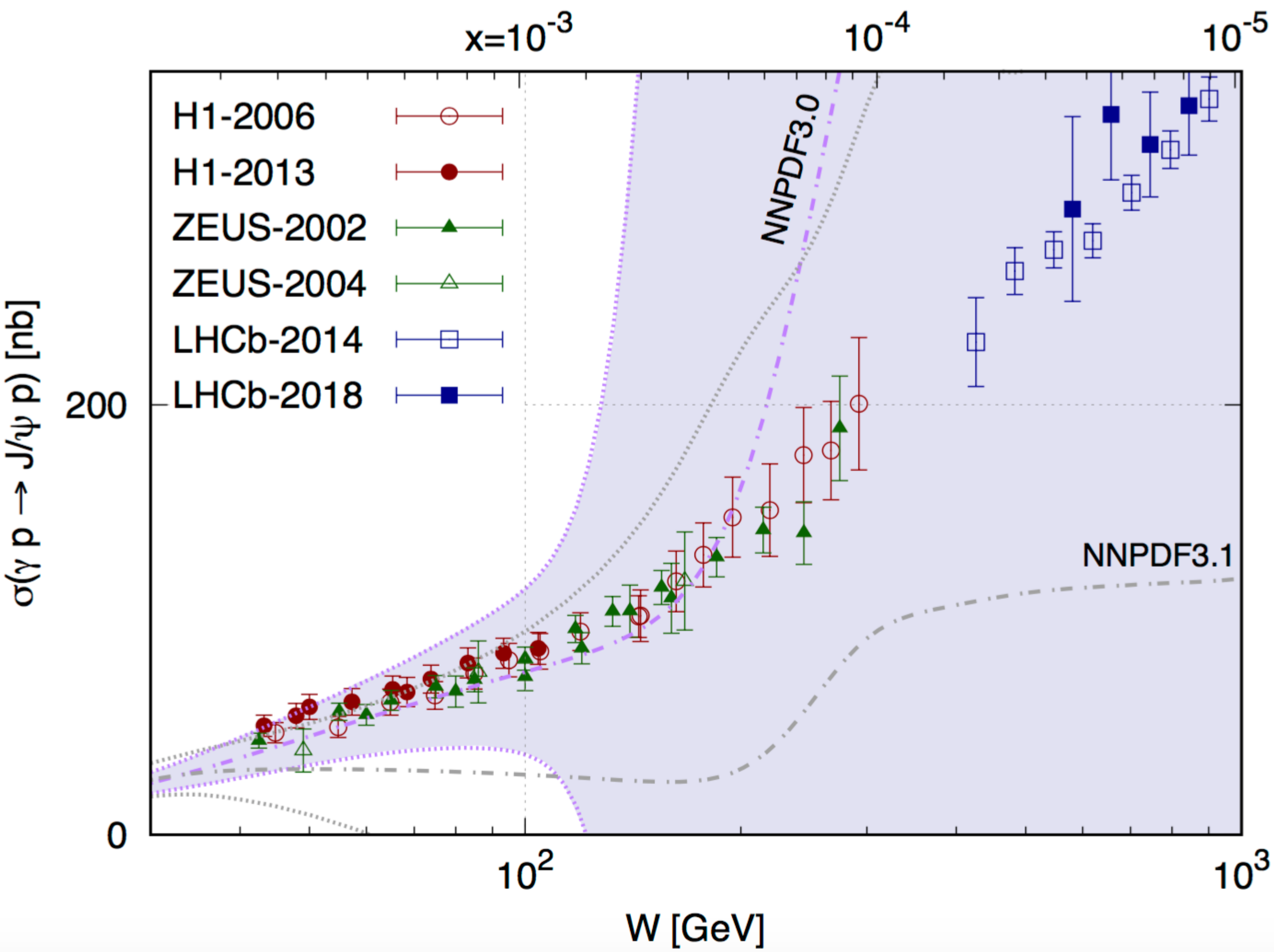
Repeat Disclaimer:

Convoluting with existing global partons. Here, MMHT14, NNPDF3.0 & CT14

$$\frac{\mathrm{Re}\mathcal{M}}{\mathrm{Im}\mathcal{M}} \sim \frac{\pi}{2}\lambda = \frac{\pi}{2}\frac{\partial \ln \mathrm{Im}\mathcal{M}/W^2}{\partial \ln W^2} \quad \text{with} \quad \mathcal{M} \sim x^{-\lambda}$$

Error budgets: errors due to parameter variations in global fits >> experimental uncertainty and scale variations in the theoretical result

…… exclusive data now in a position to readily improve global analyses



Exclusive LHCb data will constrain small x growth whilst *exclusive* HERA data will improve determination of partons in regime with data constraints already from diffractive DIS HERA data

CAF, S.P.Jones, A.D.Martin, M.G.Ryskin, T.Teubner, 1907.06471, 1908.08398

Extraction of low x gluon PDF via exclusive J/psi

Left

Approach 1: Fit a low x gluon PDF ansatz to the data

Right

Approach 2: Bayesian reweight current global PDF analyses

	λ	n	$\chi^2_{\min}$	$\chi^2_{\min}$/d.o.f
NNPDF3.0	0.136	0.966	44.51	1.04
MMHT14	0.136	1.082	47.00	1.09
CT14	0.132	0.946	48.25	1.12

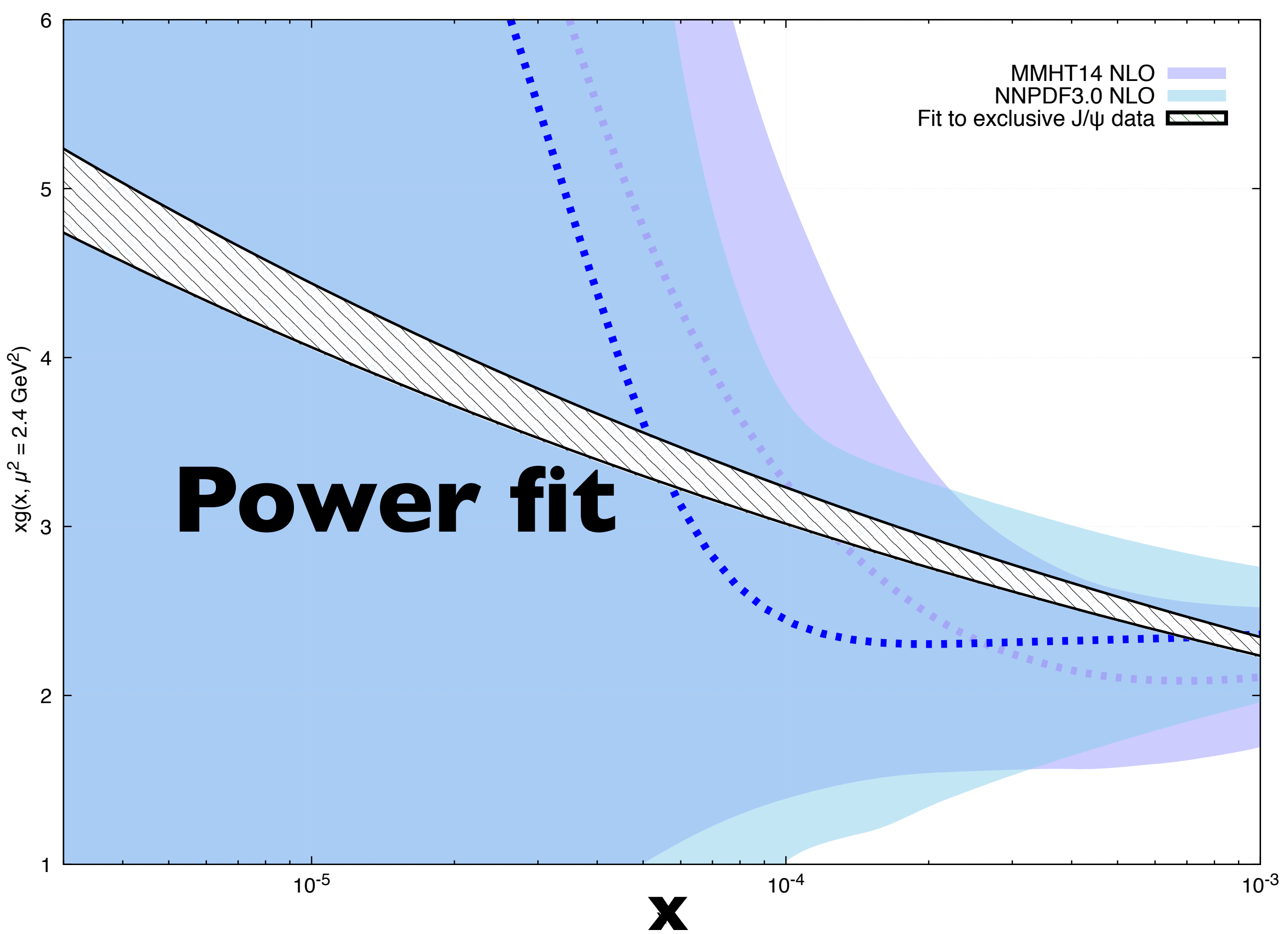
$$xg^{\text{new}}(x,\mu_0^2) \;=\; nN_0\,(1-x)\,x^{-\lambda}$$

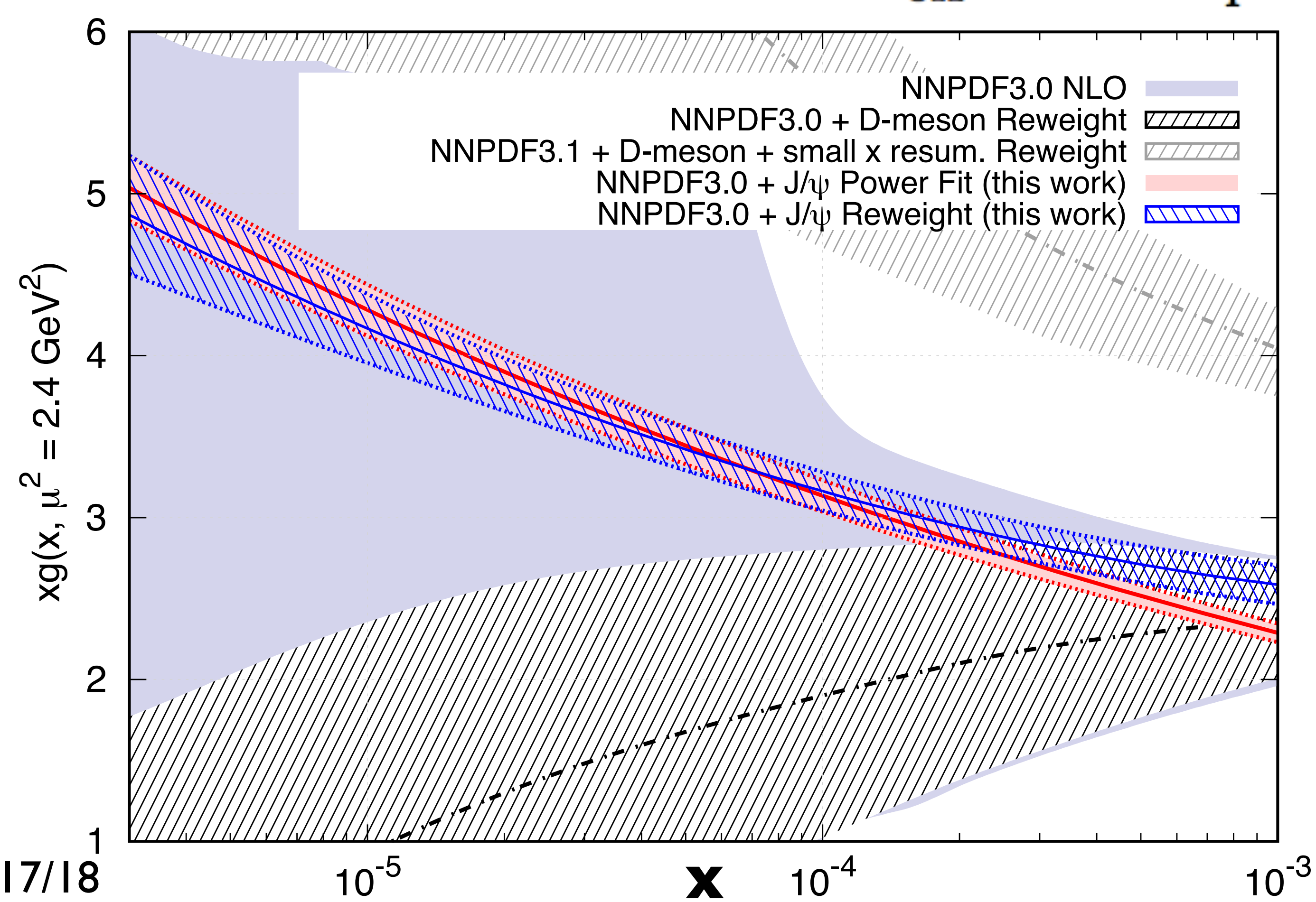
lambda = 0.136 +/- 0.006

n = 0.966 +/- 0.025

CAF, A.D.Martin, M.G.Ryskin, T.Teubner, 2006.13857

$N_{\text{eff}} \ll N_{\text{rep}}$





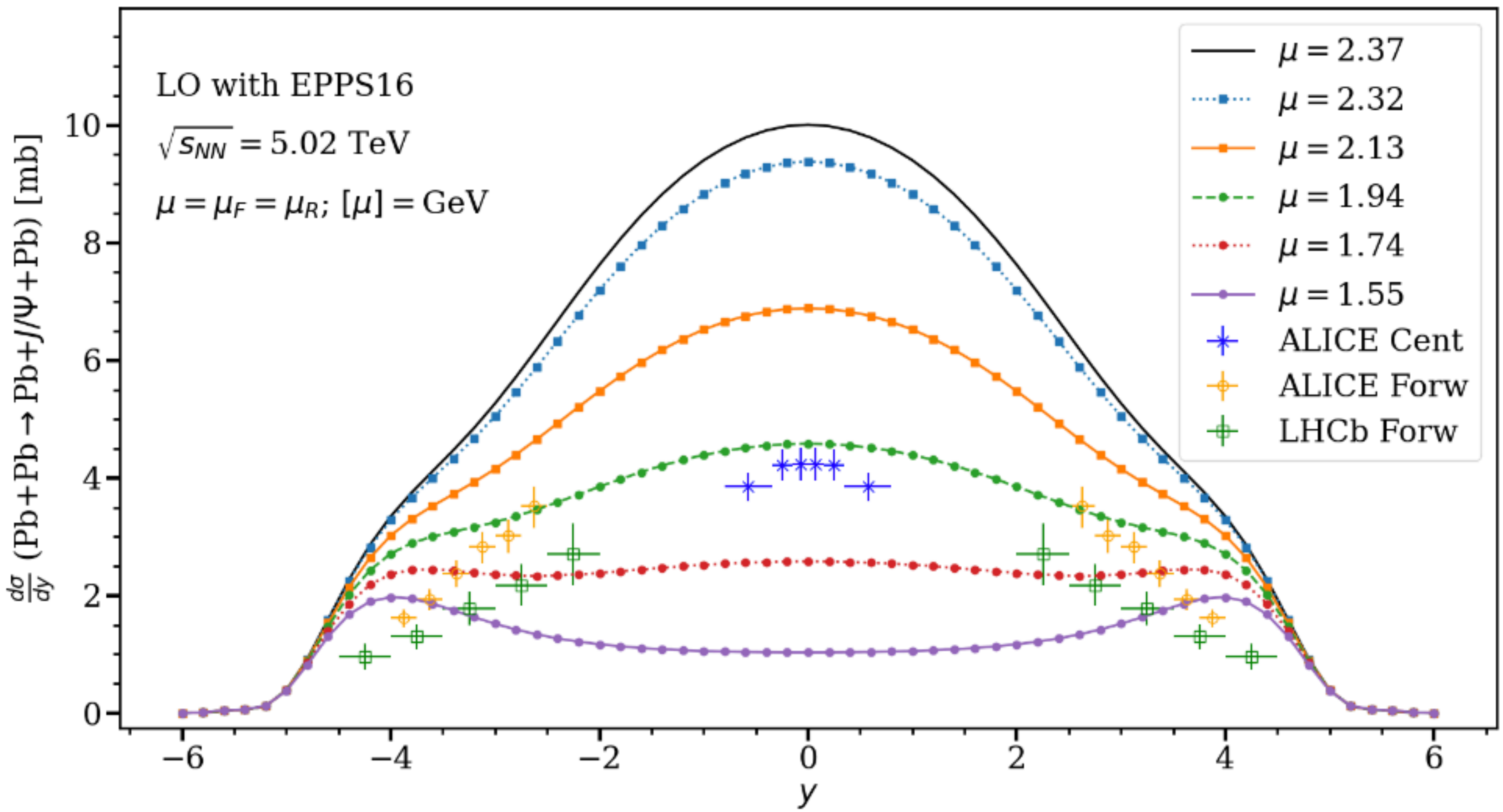
Summary

- Conventional MSbar NLO coll. fact. result unreliable and unstable
- Systematic taming via 'Q0' cut and resummation of large logarithmic contributions collectively reduce wild scale variations
- Predictions at cross section level have a good stability and central values in agreement of data within 1sigma error bands
- Large difference between predictions based on global PDFs in LHCb regime
- Reconciliation at HERA energies -> motivated a low x and low scale gluon PDF extraction via two approaches and shown to be consistent
- Upshot: In a position to finally use exclusive J/psi data in a global fitter framework

Thank you

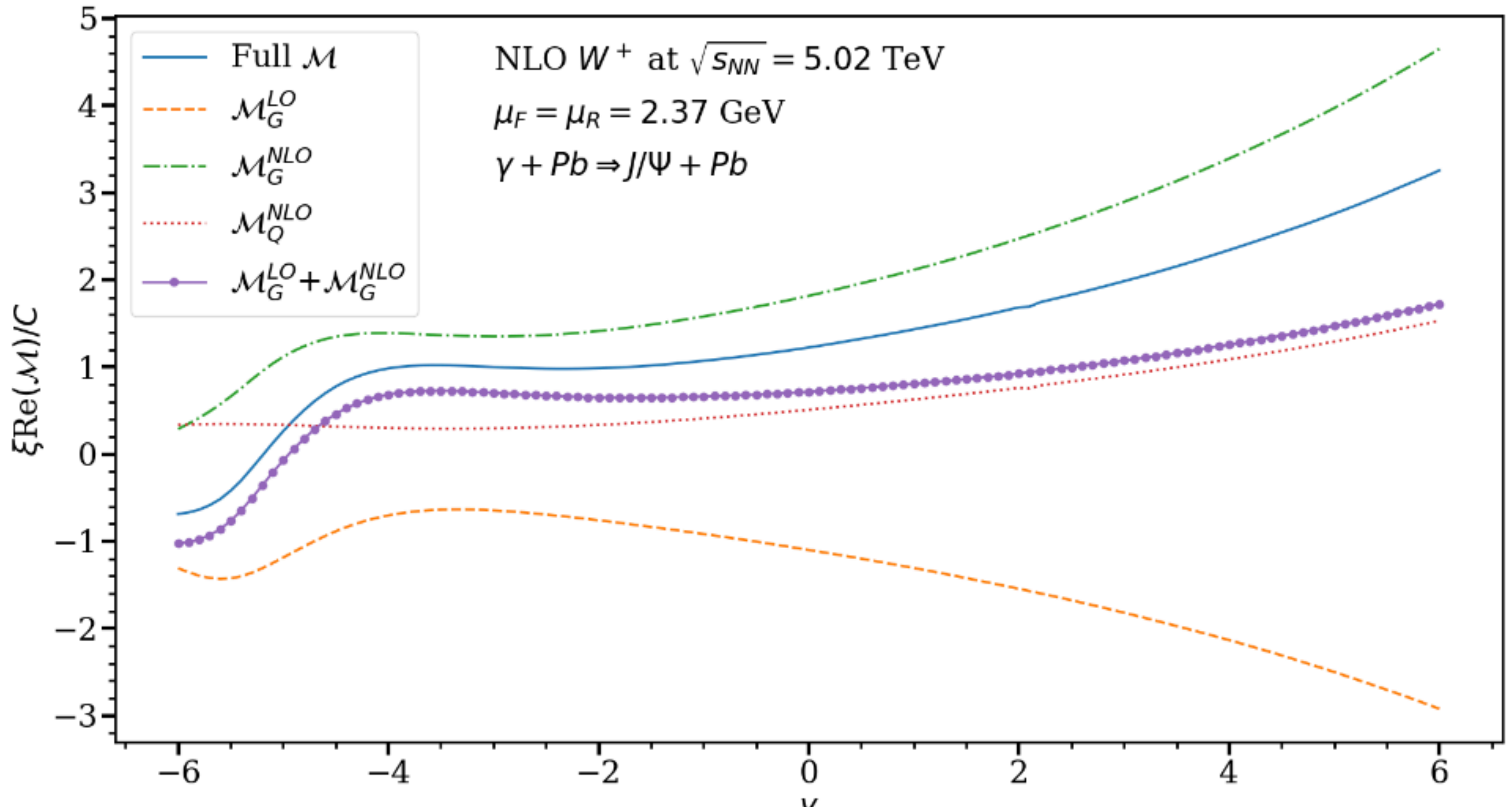
Backups

LO Scale dependence & comparison to data

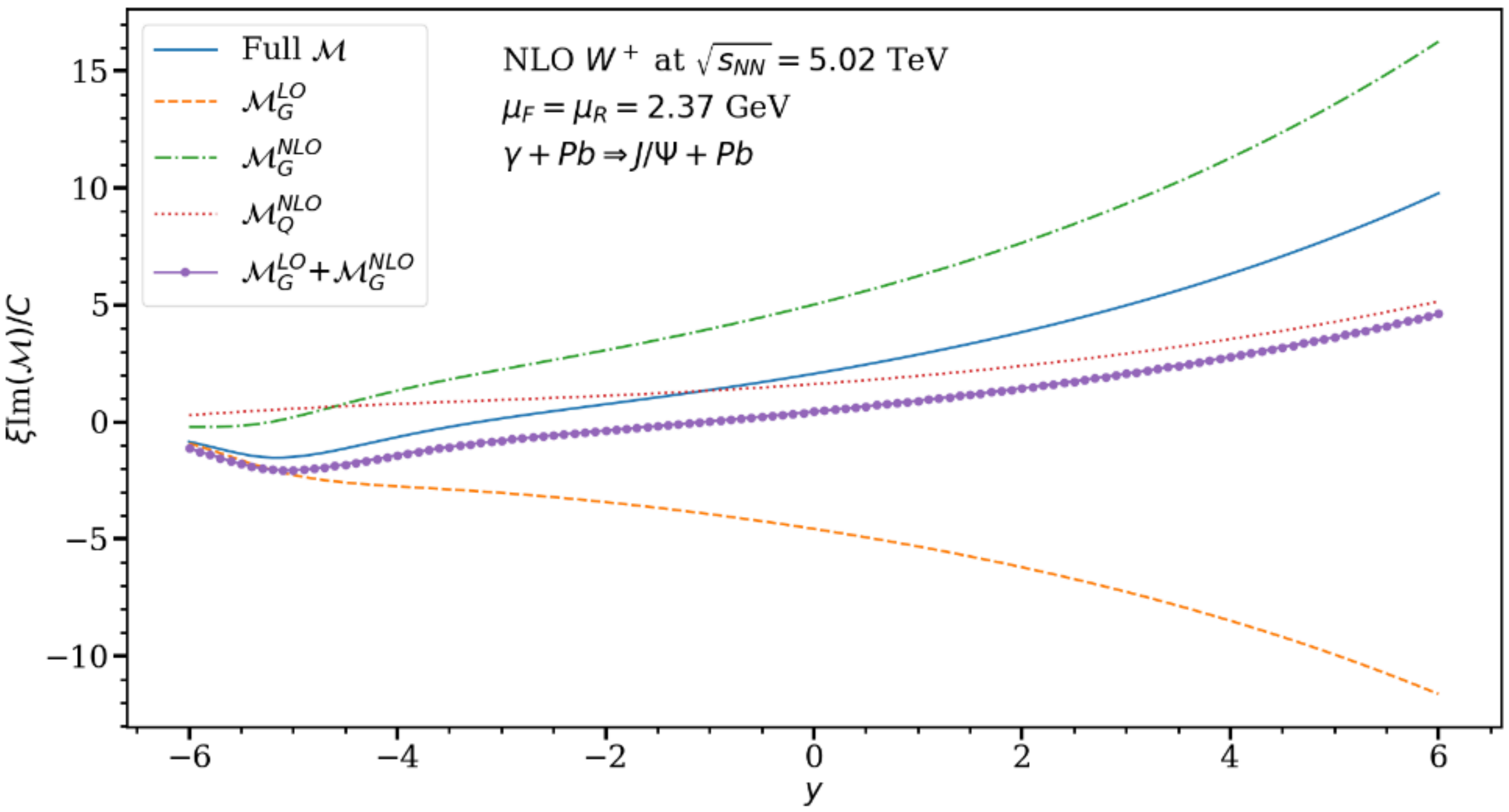


LO and NLO amplitudes

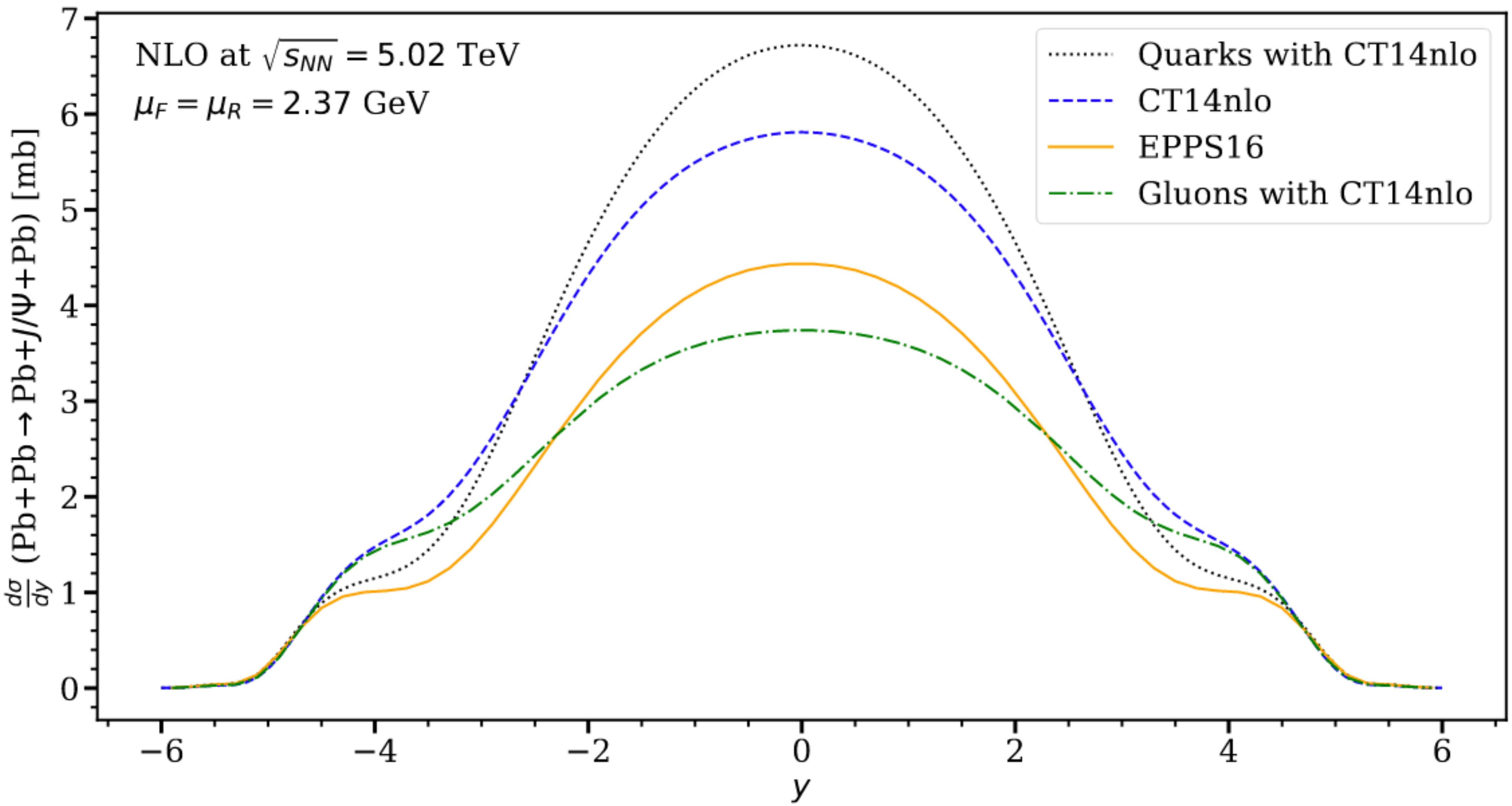
Re:



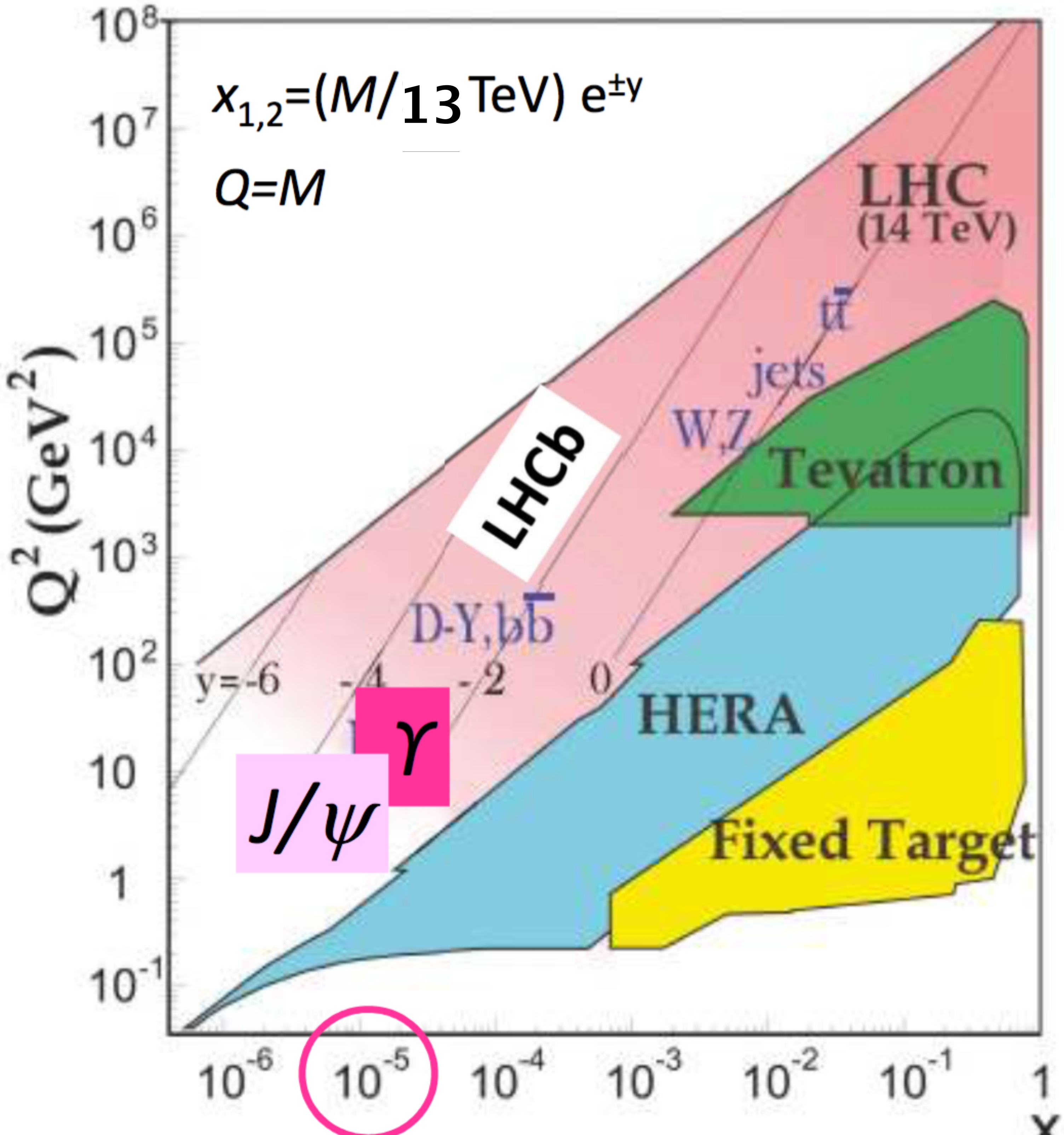
Im:



CT14nlo and EPPS16



Kinematic coverage

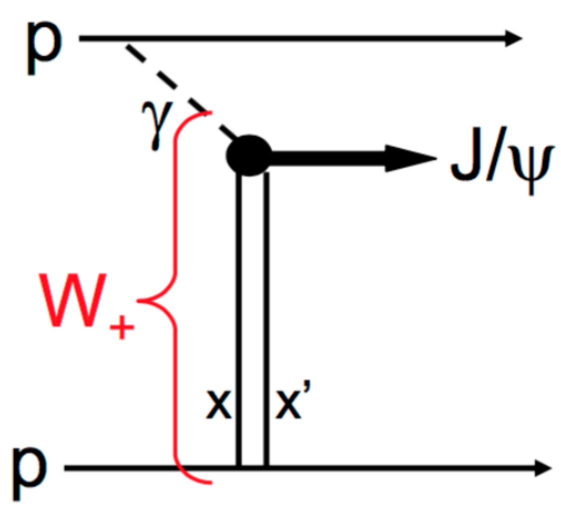


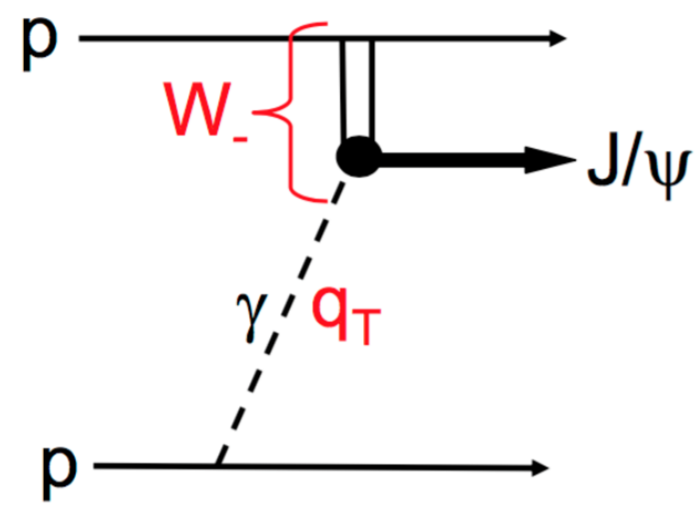
LHCb with $2 < y < 4.5$ can probe gluon down to $x \sim 10^{-5}$

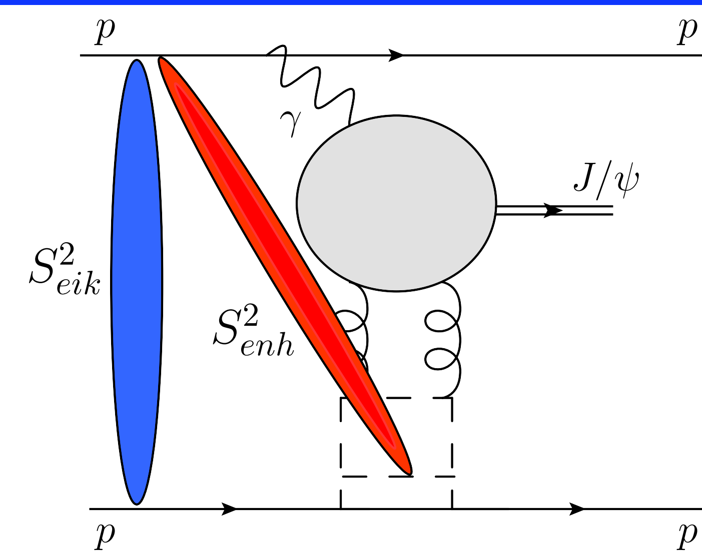
exclusive J/ψ, Υ
[$Q=M_V/2$ (scale)]

Why are these LHCb data not used in global PDF fits ??

General Set up and assumptions







LHCb data

$$\frac{d\sigma(pp)}{dy} = S^2(W_+)\left(k_+\frac{dn}{dk_+}\right)\sigma_+(\gamma p) + S^2(W_-)\left(k_-\frac{dn}{dk_-}\right)\sigma_-(\gamma p)$$

survival probability factors

LHCb 'data'

photon flux

HERA gives W-

$$W_\pm^2 = M_{J/\psi}\sqrt{s}e^{\pm|y|} \quad \Rightarrow x_\pm = \begin{cases} 10^{-5} \\ 0.02 \end{cases} \quad \text{at } y=4,\ \sqrt{s}{=}13 \text{ TeV}$$

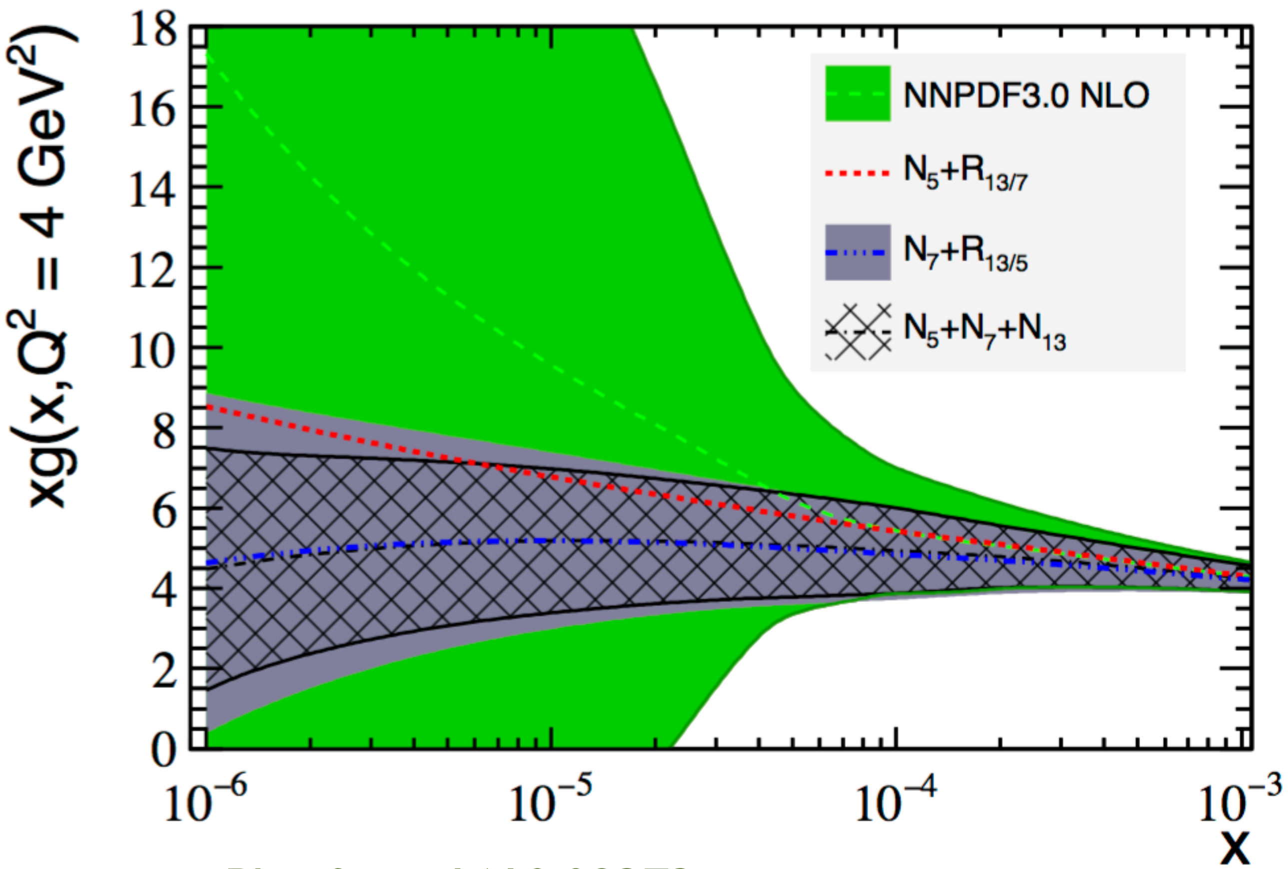
Constraints from inclusive D meson production data

Idea: Construct ratios of observables in y and p_t bins to combat various uncertainties

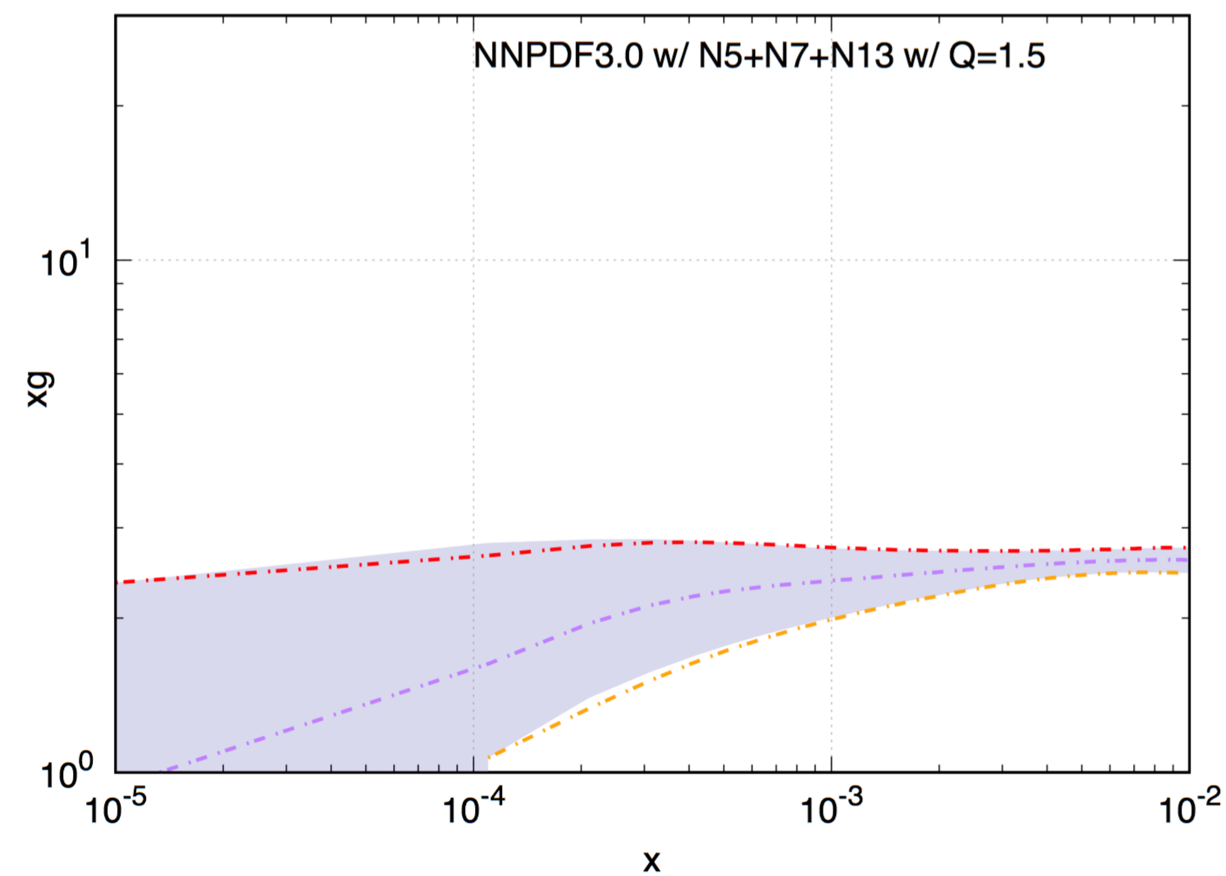
$$N_X^{ij} = \frac{d^2\sigma(\text{X TeV})}{dy_i^D d(p_T^D)_j} \Big/ \frac{d^2\sigma(\text{X TeV})}{dy_{\text{ref}}^D d(p_T^D)_j}$$

$$R_{13/X}^{ij} = \frac{d^2\sigma(13\text{ TeV})}{dy_i^D d(p_T^D)_j} \Big/ \frac{d^2\sigma(\text{X TeV})}{dy_{\text{i}}^D d(p_T^D)_j}$$

→ find decreasing gluon at the lowest x they may probe



Plot from 1610.09373



Tension with the J/psi data

We need a much harder gluon at low x to describe the exclusive J/psi LHCb data.

What's the reconciliation?

Tension with the J/psi data

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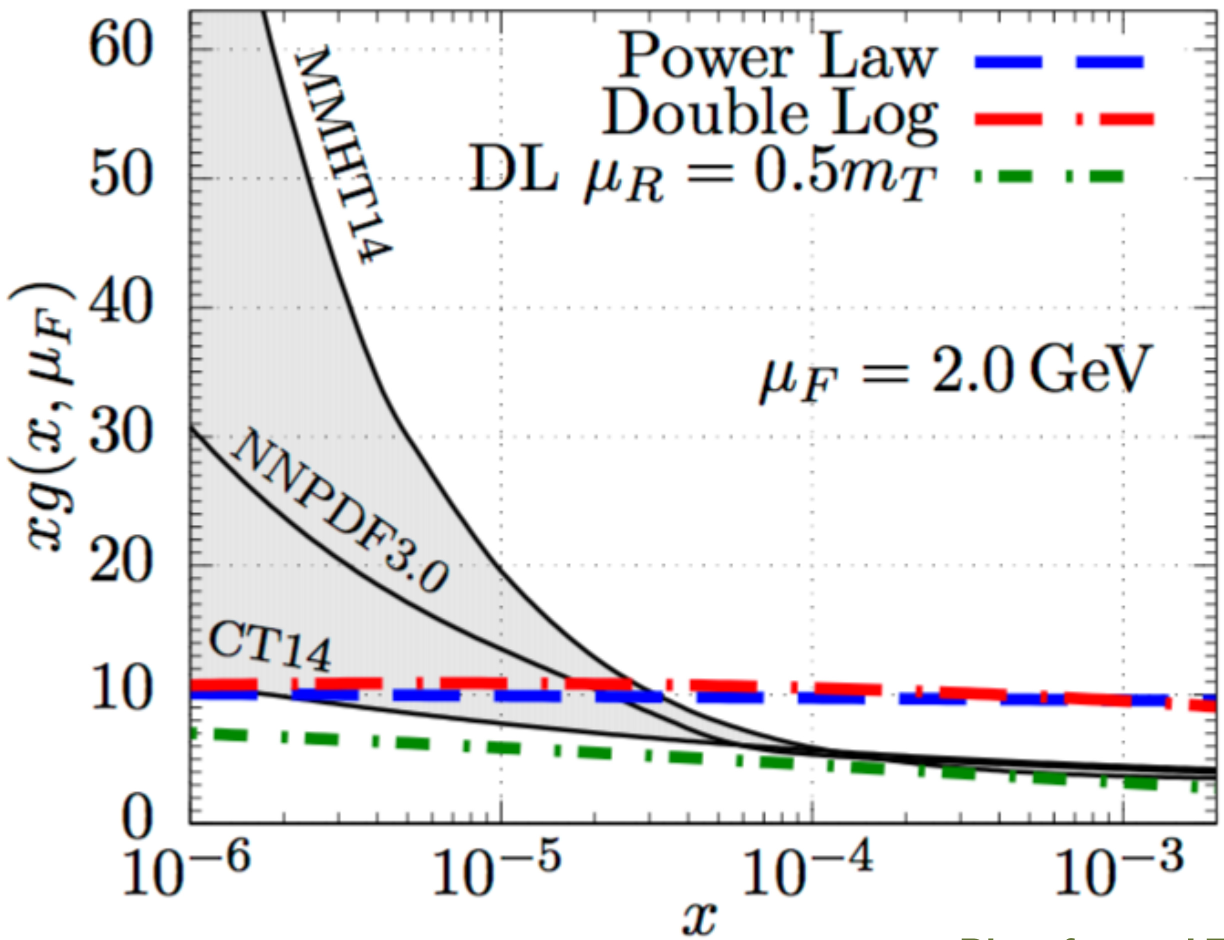
What's the reconciliation?

Indications of **inconsistencies** in the inclusive D experimental measurement

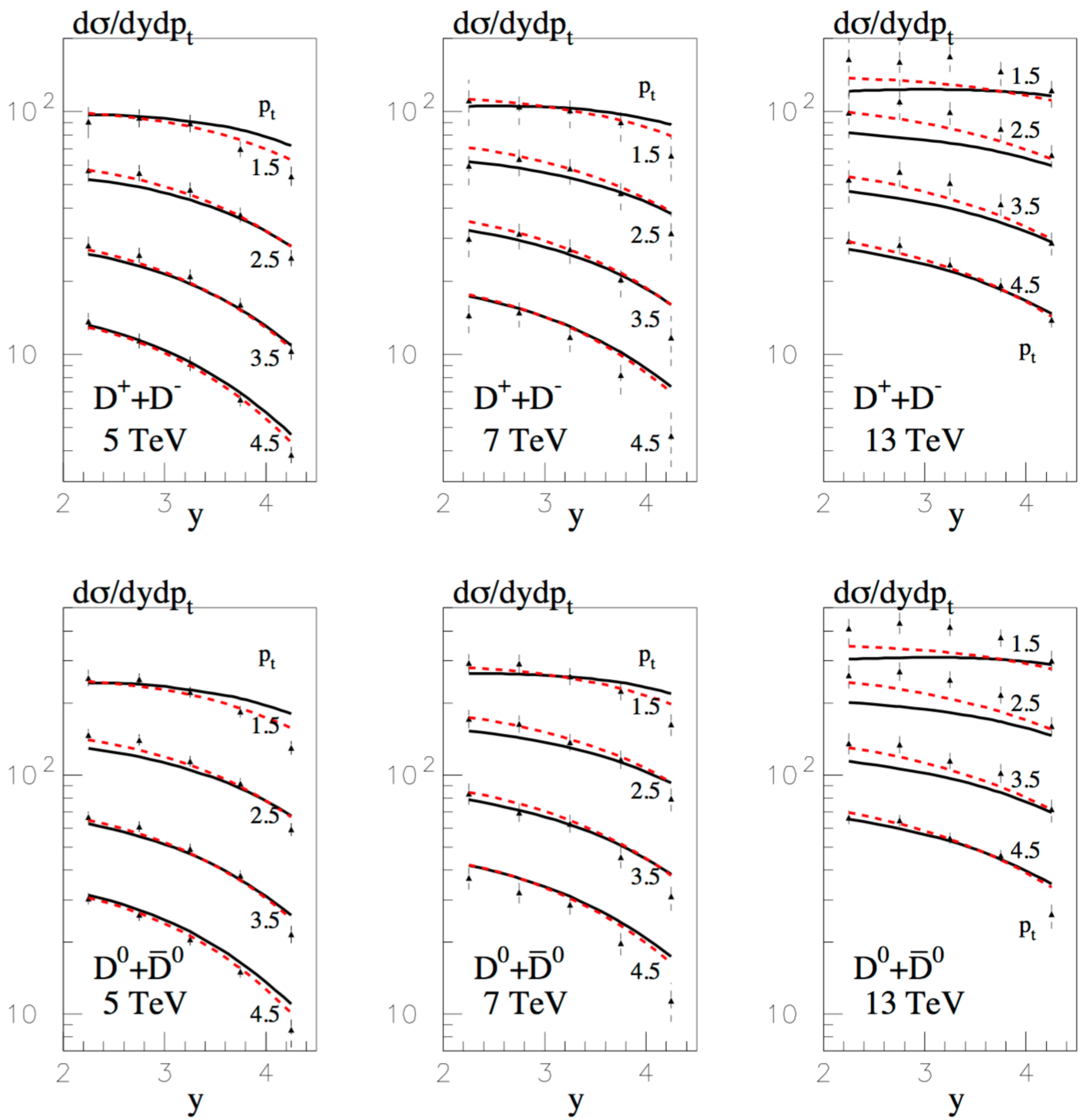


Plot from 1712.06834

$$xg(x) = N\left(\frac{x}{x_0}\right)^{-\lambda}$$

$$xg(x,\mu^2) \; = \; N^{\mathrm{DL}}\left(\frac{x}{x_0}\right)^{-a}\left(\frac{\mu^2}{Q_0^2}\right)^{b}\exp\left[\sqrt{16(N_c/\beta_0)\ln(1/x)\ln(G)}\right]$$

Rapidity and energy dependence of open charm cross section



Plot from 1712.06834

- Need *slower* increasing gluon with decreasing x to describe rapidity dependence
- Need *faster* increasing gluon with decreasing x to describe energy dependence

y ~ ln(1/x) !!

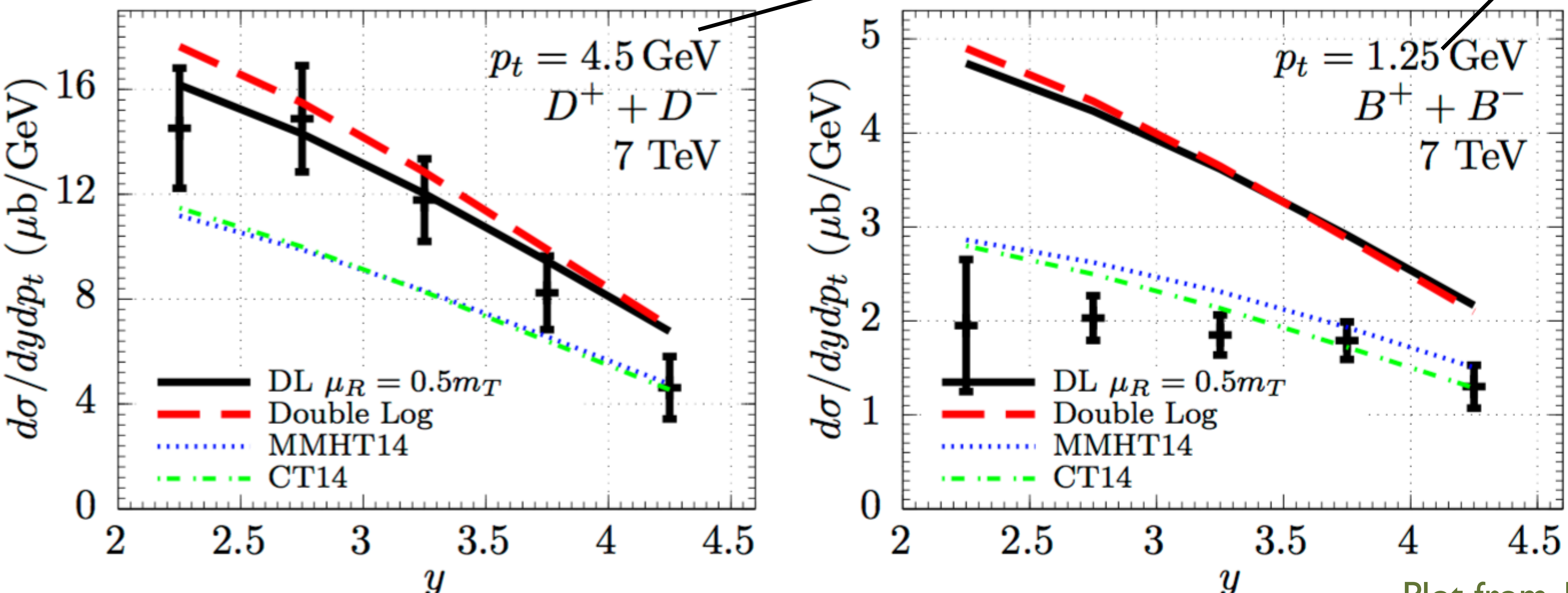
dash Q_0=1 GeV and $\mu_F = \mu_R = 0.85 m_T$

solid $\mu_f = \mu_R = 0.5 m_T$ and Q_0=0.5 GeV

Open beauty results

B sector has something to say…

p_t chosen to sample gluon at same factorisation scale and x



Plot from 1712.06834

Gluon found through fit to D meson data fails to describe the B meson distribution

Should we really trust the decreasing nature of the low scale, low x gluon obtained via fit to LHCb open charm data?

Shuvaev Transform cont.

The conformal moments H_i^N of the GPDs are given by

$$H_i^N \equiv \int_{-1}^{1} \mathrm{d}x R_{N,i}(x_1, x_2) H_i(x, \xi), \qquad i = q, g,$$

Ohrndorf, 82

The conformal moments are polynomials in even powers of ξ,

$$H_i^N = \sum_{k=0}^{\lfloor (N+1)/2 \rfloor} c_{k,i}^N \xi^{2k} = c_{0,i}^N + c_{1,i}^N \xi^2 + c_{2,i}^N \xi^4 + \ldots, \qquad , \; c_{0,i}^N = f_i^N$$

Leading term is Mellin moment of PDF

- Provided inverse exists then can relate GPDs to PDFs with suppression of order xi (i.e. good low x approx)

Shuvaev Transform cont.

Widely debated, certain conditions needing upheld, e.g lack of singularities in Re N > 1 plane

e.g Diehl, Kugler, 08

Regge theory considerations => condition met Martin, Nockles, Ryskin, Teubner, 09

- Can check in physically motivated ansatz, e.g MSTW2008 global partons input parametrisation

Martin, Stirling, Thorne, Watt, 09

$$xg(x, Q_0^2) = A_g x^{\delta_g}(1-x)^{\eta_g}(1+\epsilon_g\sqrt{x}+\gamma_g x) + A_{g'}x^{\delta_{g'}}(1-x)^{\eta_{g'}}.$$

Expand about x ~ 0

$$xg(x, Q_0^2) = A_g x^{\delta_g} + A_{g'}x^{\delta_{g'}} + \dots,$$

Mellin transform:

$$\begin{aligned} xg^N(Q_0^2) &= \int_0^1 \mathrm{d}x x^{N-1}(A_g x^{\delta_g} + A_{g'}x^{\delta_{g'}}) + \dots \\ &= \frac{A_g}{N+\delta_g} + \frac{A_{g'}}{N+\delta_{g'}} + \dots, \end{aligned}$$

Fits to data (including 1sig. errors) suggest $\delta_g > -1$ and $\delta_{g'} > -1$

- Shuvaev transform describes HVM and GDVCS data well

Kumericki, Muller, 10